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(NASA-CR-170751) HIGH-SPEED MACHINING OF
SPACE SHUTTLE EXTERNAL TANK (ET) PANELS
Final Report (Lockheed Missiles and Space
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 **Lockheed Missiles & Space Company, Inc.**
SUNNYVALE, CALIFORNIA

J. D. Hall, LEH-4
LMSC-D059404

FINAL REPORT

HIGH-SPEED MACHINING OF
SPACE SHUTTLE EXTERNAL TANK
(ET) PANELS

15 APRIL 1983

Prepared for:

National Aeronautics & Space Administration

George C. Marshall Space Flight Center

Marshall Space Flight Center, Alabama 35812

Prepared by:

Joseph A. Miller
Missile Systems Division

Contract: NAS8-34508

TASK A
FINAL REPORT

HIGH-SPEED MACHINING (HSM) OF
SPACE SHUTTLE EXTERNAL TANK (ET) PANELS

25 FEBRUARY 1983

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Marshall Space Flight Center, Alabama 35812

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Joseph A. Miller
Missile Systems Division
Lockheed Missiles and Space, Inc.
Sunnyvale, CA

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FOREWARD

Lockheed Missiles and Space Company, Inc. is pleased to submit this Task A final report to the National Aeronautics and Space Administration, Marshall Space Flight Center in accordance with Contract Number NAS8-34508. The program, summarized herein, covers Task A of the contract as it has been adjusted since originally awarded. The changes made transferred the paragraph "Identify Potential High-Speed Milling Procedures" from Task A to Task B where it is entitled "High-Speed Milling Procedures and Times," and descoped the Task A paragraphs entitled "Analysis of Present Manufacturing Methods" and "Time and Motion Study."

This submission is not intended to duplicate the Task B report and documents primarily the findings of the Task A activities.

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Section 1
INTRODUCTION

The External Fuel Tank (ET) of the Space Shuttle (Figures 1-1 and 1-2) is not recovered after launch and a new one must be provided for each launch. Currently, the external "skin" panels of the tank are produced by machining from solid wrought 2219-T87 aluminum plate stock approximately 1-3/4 inch thick. The reduction of costs in producing External Fuel Tank panels is obviously of particular significance.

This study, which is divided into Tasks A and B, was initiated to investigate the feasibility of increasing production rates and decreasing costs of the panels through the application of high-speed machining (HSM) techniques.

1-1 TASK A OBJECTIVES

Task A (the subject of this report) was designed to study potential production rates and project cost savings achieved by converting the current conventional machining process in manufacturing Shuttle External Tank panels to HSM techniques. Savings were to be projected from the comparison of current production rates with HSM rates and with rates attainable on new conventional machines. The HSM estimates were also to be based on rates attainable by retrofitting existing conventional equipment with high-speed spindle motors and rates attainable using new state-of-the-art machines designed and built for HSM.

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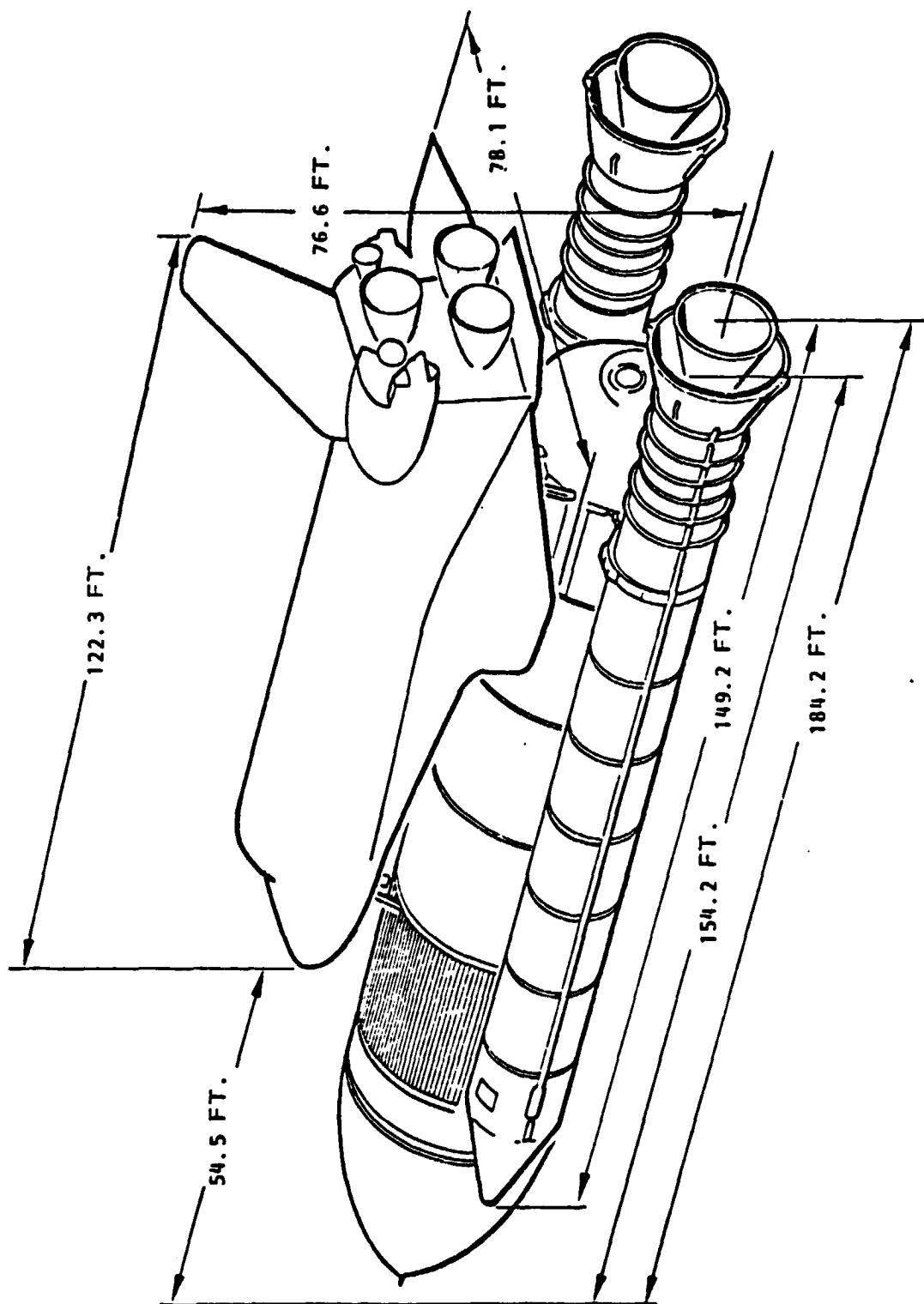


Figure 1-1. Space Shuttle Attached to External Fuel Tank

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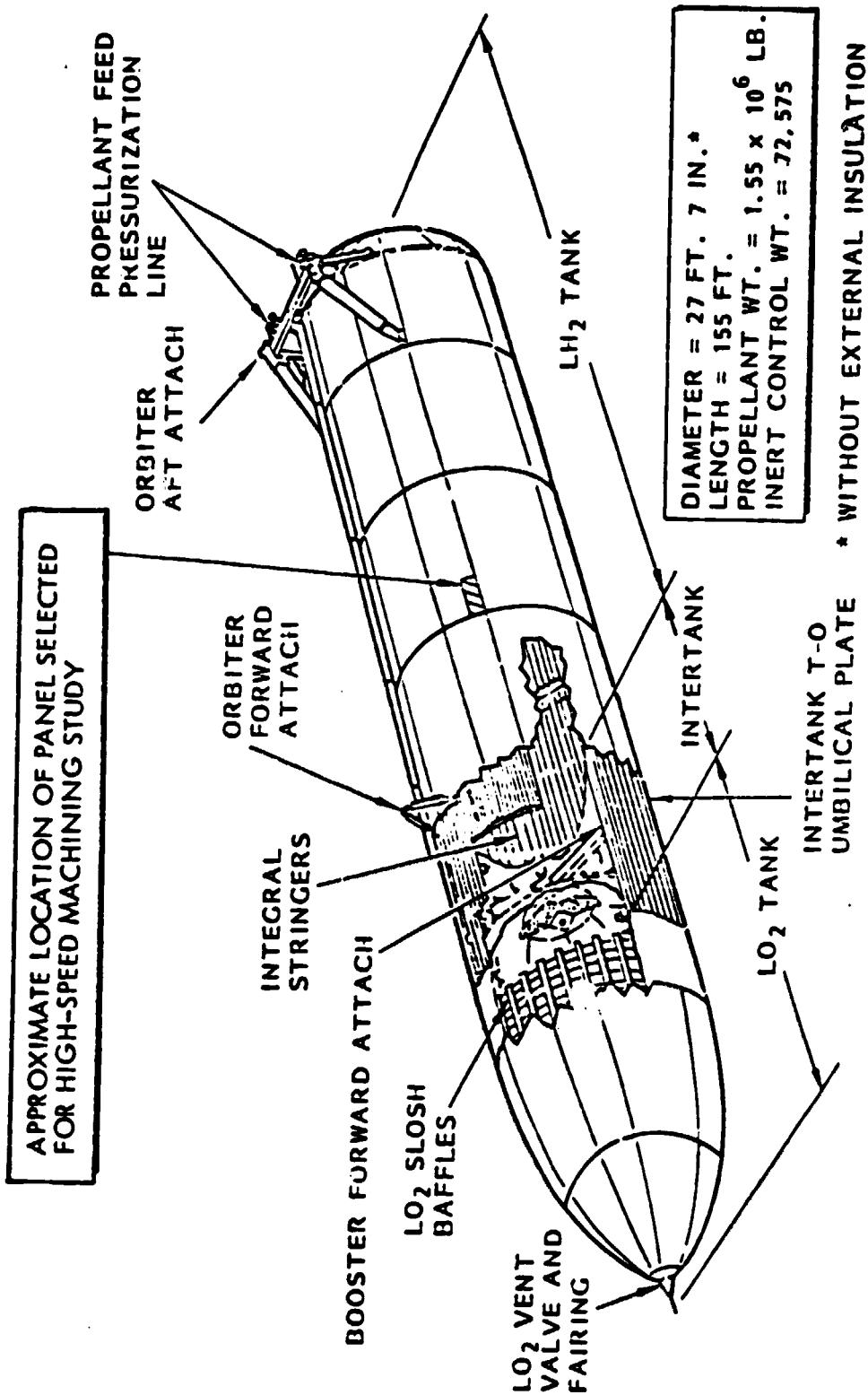


Figure 1-2. Detail of Space Shuttle External Fuel Tank

Section 2
SUMMARY - TASK A

Lockheed Missiles and Space Company, Inc., contracted with the Marshall Space Flight Center at Huntsville, Alabama to study the feasibility of transferring the high-speed machining (HSM) techniques developed at LMSC for milling aluminum missile parts to the machining of Space Shuttle External Fuel Tank Panels.

The goals of Task A were to:

- a. Investigate current machining techniques.
- b. Using a production rate of 64 panels per month for 84 months as a basis, compare current production rates and costs to projections based on retrofitting present equipment to HSM.
- c. Compare current production rates and costs to projections based on replacing present equipment with new HSM equipment.
- d. Compare current production rates and costs to projections based on replacing present equipment with new conventional equipment.
- e. Perform an economic trade-off analysis comparing various machine options.

A gantry type milling machine presently being used to machine Shuttle Fuel Tank panels was utilized as a basis for comparison in this study. Information was gathered from several machine tool builders active in HSM, from HSM spindle manufacturers, and from machine tool rebuilders.

Projected machining times and labor and machine investment costs were determined for 41 specific machine tool configurations.

Findings of the study indicated that significant improvements in machining production rates and cost over the present machine used as a basis for comparison can be realized with new currently available state-of-the-art HSM equipment. Using proven HSM equipment, production rates could be increased from 3.9 panels per month currently to 73.5 panels per month. This increase in production level could be accomplished using a one panel wide, two panel long gantry-type mill with two 75 hp, 9,000 rpm spindles. The use of advanced HSM

equipment (not fully proven but at a high confidence level) with two 100 hp 12,000 rpm spindles would increase production rates to 86.6 panels per month. Projected rates for two panel wide machines are even higher, but the costs are also higher. Projected rates for unproven HSM 150 hp, 24,000 rpm spindles for both one and two panel width machines would push production rates still higher if appropriate cutters were available.

By retrofitting two 100 hp, 12,000 rpm HSM spindles on the present gantry-type mill, production rates could be increased from 3.9 panels to an estimated 43.3 panels per month. Two machines thus converted would be needed to achieve the 64 panel per month production requirement.

New conventional machines could be used to increase production rates from 3.9 currently to 87.6 panels per month. This level could be accomplished with a two panel wide, two panel long gantry-type mill and four 150 hp, 3,600 rpm spindles.

The HSM panel machining times determined from the actual 4 foot by 8 foot panel section machining performed in Task B correlated very closely with the machining times projected in Task A. As an example, 6.0 hours was projected in Task B to machine a full-size panel using a single 75 hp, 9,000 rpm spindle machine. Using the detailed procedures determined in Task A, 5.9 hours was estimated for the same situation.

Areas limiting production levels and that require further development are cutters, chip removal, and panel loading and unloading.

Section 3
TASK A EFFORT

The major efforts involved in Task A are as follows:

- 1) Survey present facilities.
- 2) Gather data on conventional machine and determine cost of conversion to HSM and projected schedule.
- 3) Obtain conventional machining operation steps and times.
- 4) Assess new machines.
- 5) Determine cost and delivery schedule for new conventional machine(s).
- 6) Determine cost and delivery schedule for HSM machines.
- 7) Determine barrel panel machining times for new conventional and new HSM machines.
- 8) Perform Economic Trade-Off Analysis comparing various machine options.
- 9) Produce HSM implementation plan for each option.
- 10) Write a final report.

4 TASK A TECHNICAL APPROACH

Following is a summarized description of the detailed steps involved in the Task A study.

4-1 SURVEY OF PRESENT FACILITIES

A visit was made to an existing machine vendor where some of the Shuttle External Tank panels are currently machined. The panel machining operation taking place on a gantry-type mill was briefly observed. Following is a compilation of the information gathered regarding the machine and the various machining parameters involved in milling the panel.

Machine: Gantry type mill (in service only 6 months since major rebuild)
(Navy owned)

144" x 480" table

X axis = 480" (40')

Y axis = 144" (12')

Z axis = 12" (1')

Wilson 20 hp, 1800/3600 rpm, 440v, 3 phase spindle motor (only 13 hp available due to electrical overloading condition)

Axes . tions at 240 ipm rapid and 200 ipm programmable (originally but currently capable of 200 ipm rapid and 150 ipm programmable All axis drives (originally hydraulic) have been replaced with dc electric drives

The gantry drive motors were:

Inland Motors
Industrial Drive Division
Radford, Virginia
Model TTF2-5306-201-B
Ser. 81D82-50
2400 rpm max.
Cont (stall) 11v, 146 amp, 60 lb-ft.
Peak (stall) 14v, 200 amp, 82 lb-ft.

Controls: Allen Bradley Model 7320 CNC

Cutter sizes and maximum cuts:

- 1) Roughing cutter: 5-1/4" dia, 4-flute, at 3600 rpm and 12 ipm (average of .300" deep (.475 max) at full width)
- 2) Finishing cutter for bottom of pocket: same as roughing cutter but only .100" deep
- 3) T-rib cutter: 4" dia, 6-flute, .625" or .725" flute height (full width and full depth (.725) used at 3600 rpm and 40 ipm at top of T). Maximum radial depth of cut = .575".
- 4) Profiling cutter for sides to T: 2-1/2" dia, at 3600 rpm and 40 ipm. (Assumed to cut 3/8" radii at bottom of T, etc.)

This information was gathered in light of possibly retrofitting the machine to HSM capabilities in addition to gaining a better understanding of how the panels are presently being machined. In regard to a possible retrofit, the new Allen Bradley Model 7320 CNC controls and the fact that the machine had been recently rebuilt were felt to be definite positive points. A point which was felt to be negative was that the maximum programmable gantry feed was rated at 200 ipm but presently the machine was limited to operation at a maximum of 150 ipm. A second negative point was that the electrical power supply to the machine appeared inadequate and would need to be remedied.

The small (20 hp) spindle motor installed on a machine originally designed for a considerably larger motor(s) indicated that problems with machine vibration may have been experienced with the larger motor(s). If so, potential problems with retrofitting to high speed spindles could be expected.

4-2 COLLECTION OF DATA FROM MACHINE TOOL BUILDERS AND REBUILDERS

To obtain pertinent information regarding state-of-the-art HSM machines and related equipment, machine tool and HSM spindle builders were contacted who were known to be actively involved in the manufacture of HSM equipment of the size and type being studied.

Information relative to new machines capable of machining the Shuttle External Tank panels at conventional machining rates was also obtained. In all instances, details were solicited regarding machine specifications, cost, and delivery schedule.

The general approach taken was to telephone the machine tool builder assuring contact with the appropriate person and then follow up by letter with the necessary details. In several instances, personal meetings were held.

One general large machine tool rebuilder was contacted regarding the possible retrofitting of the present machine to HSM capabilities. Additional retrofit information was obtained from the original manufacturer of the machine and the Bryant Grinder Division of the Excello Corporation (builder of HSM spindle motors).

4-3 SELECTION OF GENERAL MACHINE TOOL CONFIGURATIONS

The most common general approach to machining large panels such as those used for the Shuttle External Fuel Tank (11' x 20') is to mount them on a stationary horizontal table and to mount vertical (or a combination of vertical and horizontal) spindles on a moveable gantry. Considerably less moveable mass is involved in moving a gantry over the part than in moving an entire table capable of properly supporting such large parts, especially if the table is large enough to mount more than one panel at a time.

A moveable gantry type machine with one or two spindles (Figure 4-1) machining a one panel width (11') was the first general configuration considered in the study. The machine presently being used to machine Shuttle Tank panels fits into this category.

The second general configuration of machine tool included in the study was the same as the first except with a two panel length table (Figure 4-2). The lengthened table would allow loading and unloading to take place without interrupting the machining process.

A third general configuration considered was a gantry type machine capable of machining a two panel width (22' plus) using two or four spindles (Figure 4-3). This machine configuration was considered with both single and double length tables.

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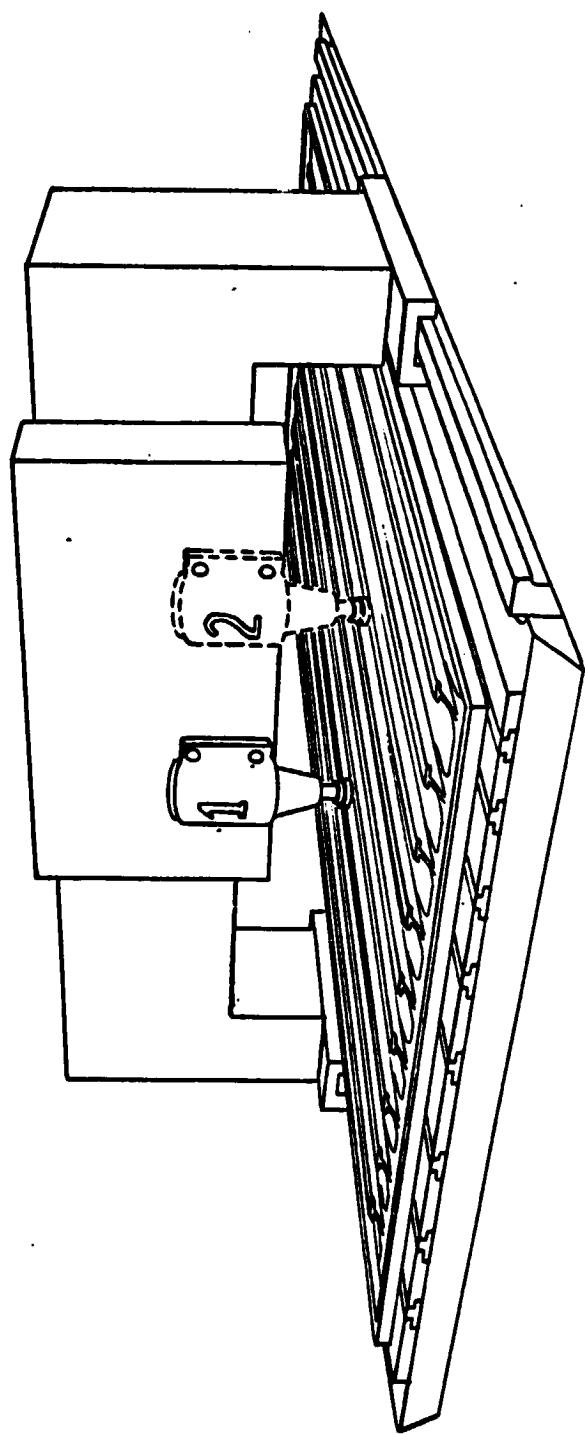


Figure 4-1. Basic Gantry-Type Machine with One or Two Spindles

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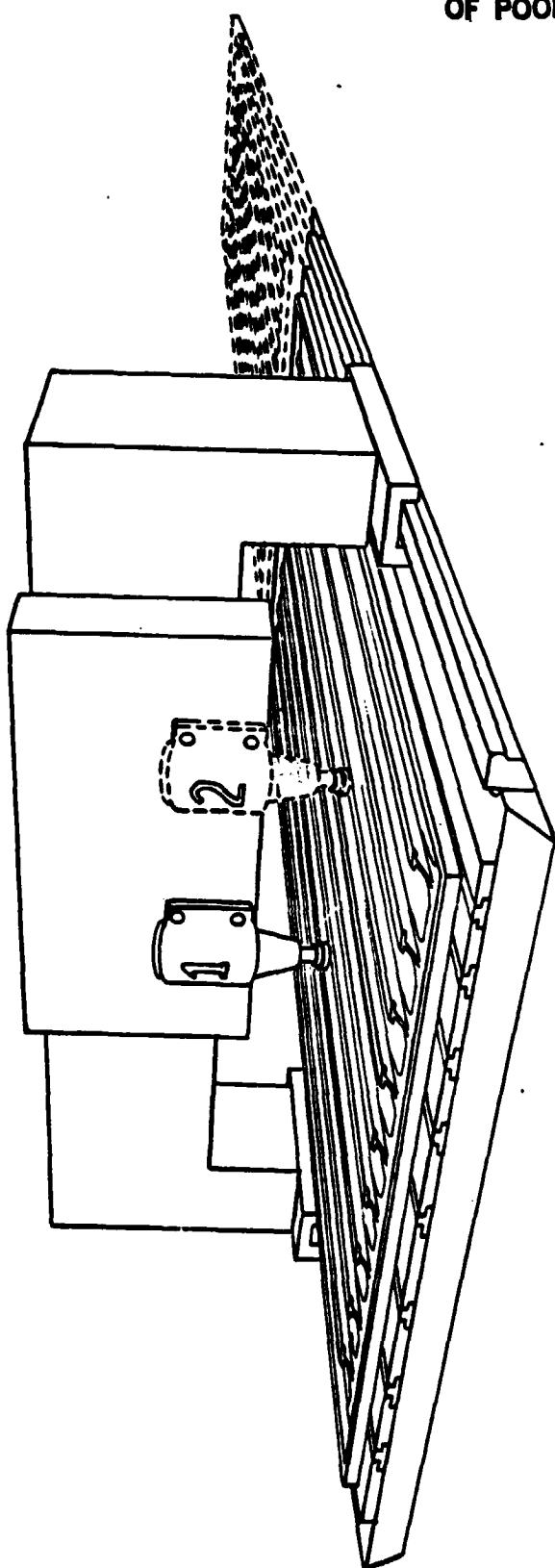


Figure 4-2. Basic Gantry-Type Machine With Lengthened Table to Allow Loading and Unloading of Second Part

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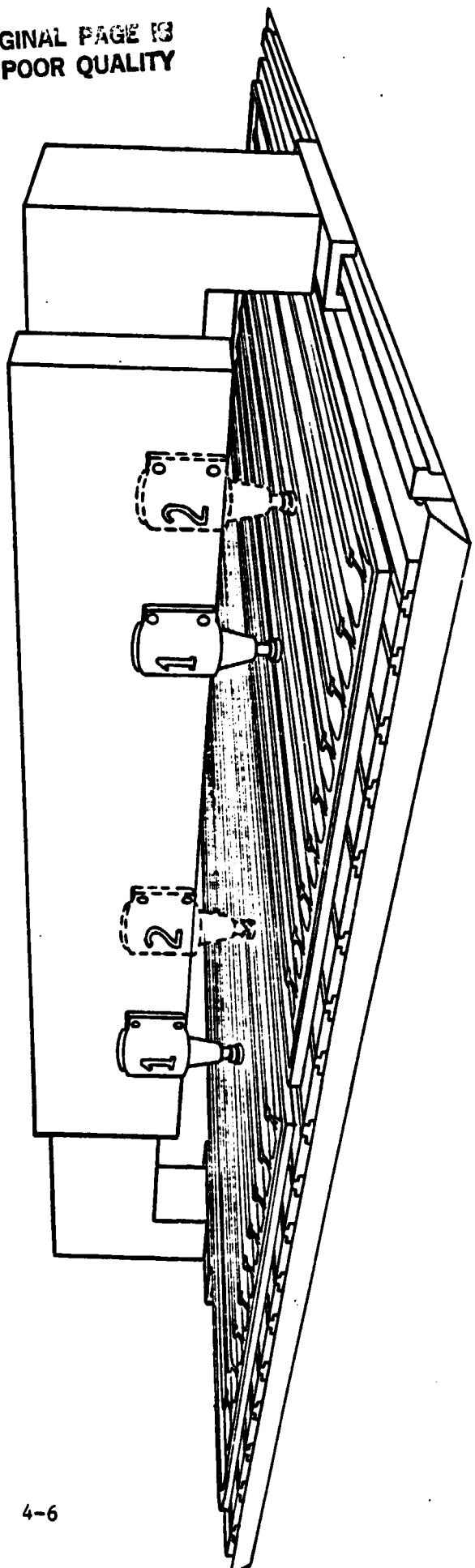


Figure 4-3. Two Panel Wide Gantry-Type Machine With Two or Four Spindles

An additional variation of the gantry type machines included in the study was a vertical spindle(s) for finish machining but separate horizontal spindle(s) for rough machining.

The fourth general configuration considered (Figures 4-4 and 4-5) involves machining panels that are mounted vertically. Either one, two, or four horizontal spindles would be used to machine one or two panels at a time. A decided advantage of mounting the panels vertically would be the relative ease of chip handling through use of a conveyor at the base of the panel.

Descriptions of the specific machine tool configurations considered in the study are included in Section 4-5.3.

4-4 DETERMINATION OF CUTTERS TO BE USED IN STUDY

The full potential of high-speed machining is still being developed. Spindles with higher rpm and horsepower are being introduced on the market. Along with these advances, however, is a definite need for more advanced cutter designs and cutter materials.

The most appropriate combinations of cutters, feeds, speeds, and depths of cut to machine the tank panels were based on the following considerations:

- a) Lockheed's background in HSM
- b) The cutters utilized and demonstrated in Task B of this contract
- c) The cutters presently in use at the existing vendor for machining tank panels.
- d) Information from sources including cutter manufacturers and machine tool builders

For the purposes of this study, a combination of both a theoretical approach (without limiting the cutting speed) and a practical approach was taken. For the theoretical approach, the assumption was made that if cutters were not yet available which could operate at the desired cutting speeds (sfpm), technology would soon develop and provide them. For the practical approach basically the same general cutter specifications (diameter and number of teeth) as are presently being used were assumed for most of the machining operations. The assumption was also made that proper adjustments in cutter

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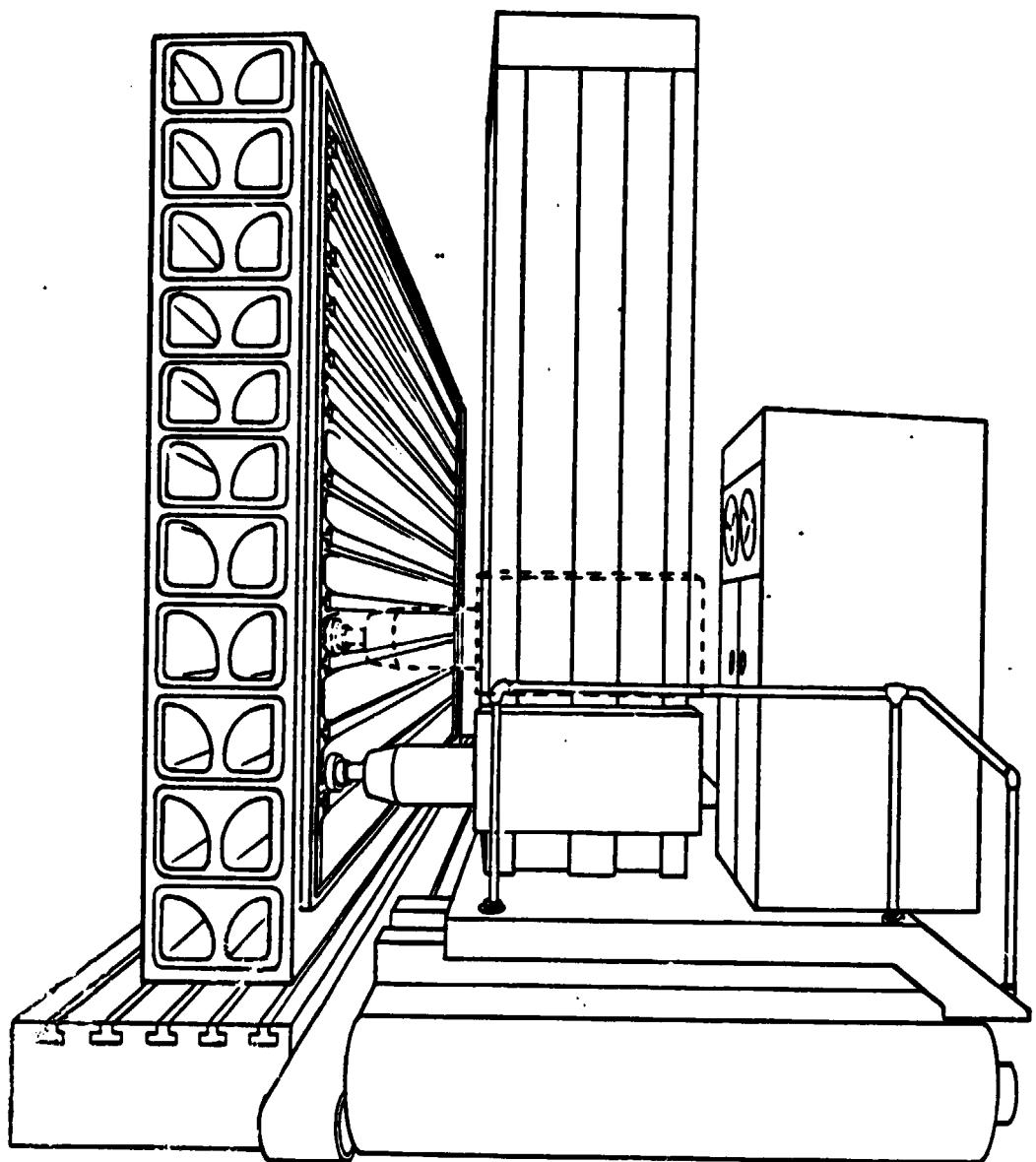


Figure 4-4. Moveable Column Machine With One or Two Spindles

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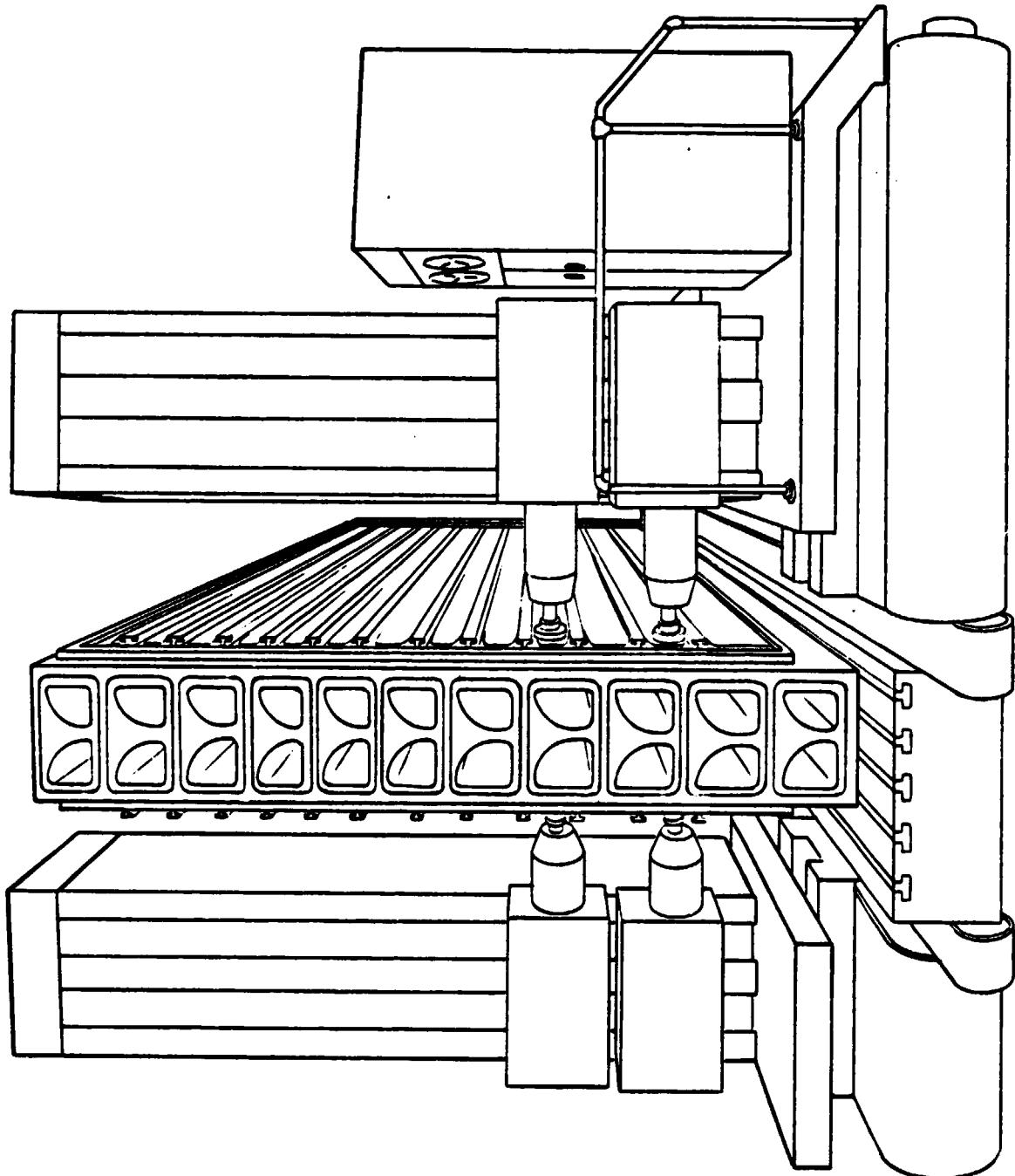


Figure 4-5. Double Moveable Column Machine With Four Spindles

angles and other details would be made to correlate with the higher cutting speeds projected in the study. However, for roughing and finishing the pockets between the T-ribs of the panels, calculations for different cutter diameters were examined (See Section 5 and Appendixes A and B for details).

Substitutions for the 5-1/4 inch diameter-four toothed cutter presently in use for both roughing and finishing included 1) a 14 inch diameter by 2.8 inch wide roughing cutter to be used with the horizontal spindle motors; 2) a 2 inch diameter, three-flute end mill for roughing, and 3) a 9 inch diameter cutter for roughing and finishing. The 9 inch cutter would have the advantage of finishing the entire width of the pocket in one pass thus eliminating tool marks and potential mismatch in the bottom of the pocket.

Except for the very highest theoretical cutting speeds, the cutters and accompanying parameters chosen were considered reasonable, but not necessarily optimum. For example, more teeth for a given diameter might improve machining time if ample chip clearance for the higher cutting speeds could still be provided.

Safety, especially at the higher cutting speeds, is an obvious concern regarding any cutter development and usage. Brazed carbide insert-type cutters were assumed for instances where insertable teeth might not be safe.

4-5 CALCULATIONS OF MACHINING TIMES AND PRODUCTION CAPACITIES

A required production rate of 64 Shuttle External Tank panels per month for 84 months starting in 1985 was specified by NASA as a basis for this study. The specific objectives of the study were to determine potential production rates and cost savings from converting to HSM techniques from the conventional machining process presently employed in milling the panels from 1.75 inch thick aluminum plate.

A consideration of all aspects of the panel production process was not within the scope of this study. The results shown are intended for comparison with only the appropriate portions of the total process. Estimated machining rates for these portions of the present process are included. Examples of machining operations not included in the comparisons are the preparation of the outside or bottom of the panels and the drilling and tapping of holes. Both of these operations can be considered to take place on other equipment and are not considered necessary to the study.

The following sub-sections describe the considerations involved in projecting machining times and production capacities for the general machine tool configurations described previously in Section 4-3.

4-5.1 Selection of Typical Panel

The panel specified for this study by the NASA Marshall Space Flight Center and their prime contractor for the Shuttle Tank, Martin Marietta, was described on Martin Marietta Drawing Number 8094200997. This panel is comparable to the one from which the demonstration sample was machined as part of Task B. It is 11' feet wide by 20 feet long and is milled from 1.75 inch thick 2219-T87 aluminum plate. Twelve longitudinal T-shaped reinforcing ribs are spaced 10.8 inches apart (Figure 4-6). An estimated 91 percent of the metal is removed.

The panel is machined from a premachined blank from which over half of the metal has already been removed. However, for the purposes of this study, all machining times including the references, are based on starting from a 1.75 inch thick solid plate.

4-5.2 Cutting Speed Limitations

As a basis for the study, projected machining rates and panel production capacities were calculated without the restraints of cutting speed limitations (expressed in surface feet per minute-sfpm). Essentially, the assumption was made that cutters were available (or would soon become available) that would allow the utilization of the full capacities of the machine tools. The tables shown in this report are based upon this assumption.

In several instances, the cutting speeds calculated were substantially above current demonstrated levels. Upon investigation, a smaller diameter cutter at the same rpm but deeper axial depth of cut was found to remove a similar amount of metal at a lower cutting speed (in currently proven range). For example, the 2 inch, 3-flute end mill used in the 150 hp, 24,000 rpm spindle machines as a roughing cutter with a .508 inch depth of cut provided similar metal removal rates as the 9 inch cutter with a .066 inch depth of cut on the same machines (Table A-1, Appendix A).

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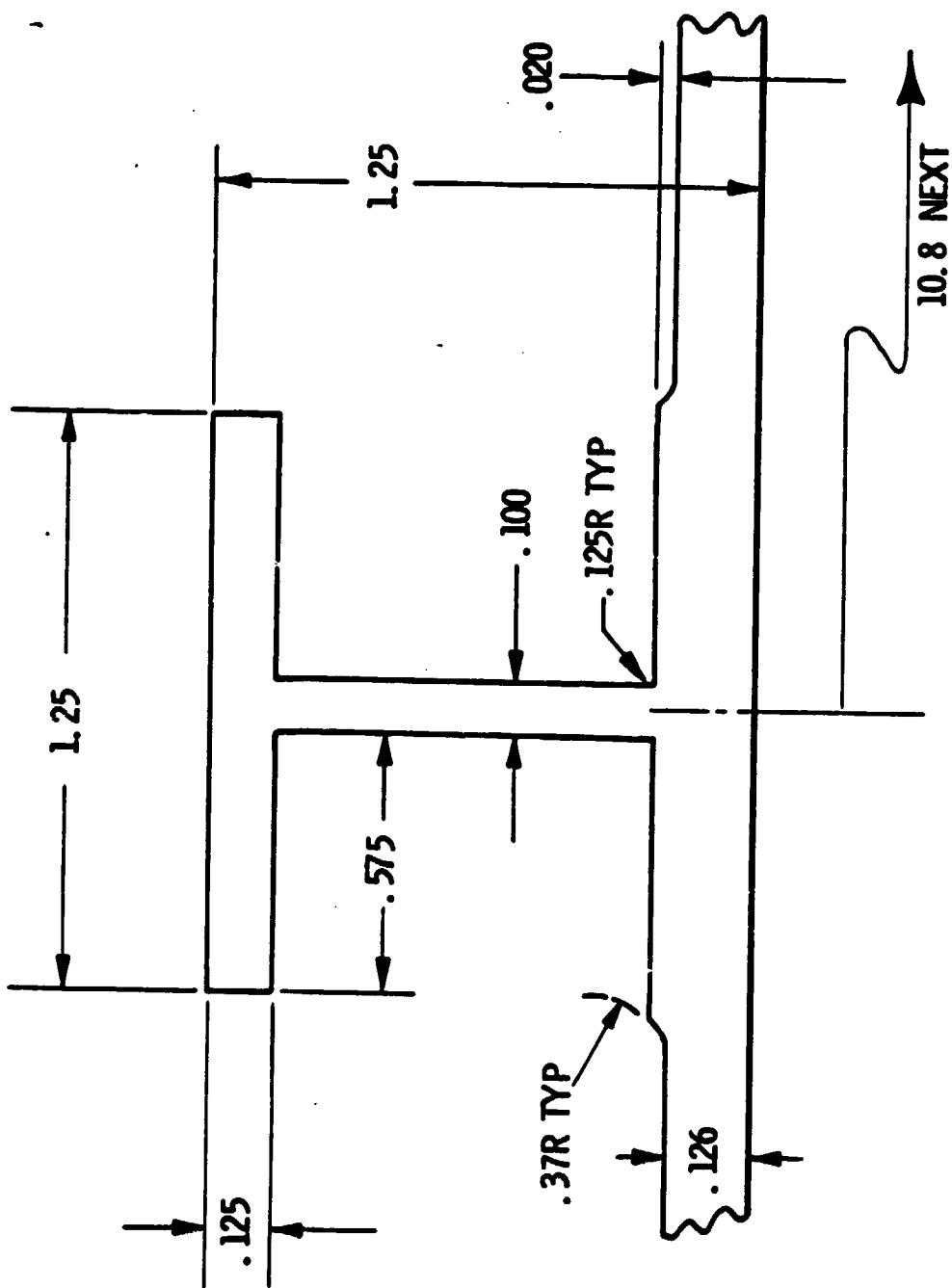


Figure 4-6. Section View of T-Rib Reinforcement of Fuel Tank Panel

The potential for obtaining cutters capable of the maximum cutting speed indicated in this study (56,549 sfpm) was pursued further. A spokesman for a major cutter manufacturer involved directly in cutter development for HSM stated that a cutter capable of machining aluminum at 56,000 sfpm is felt to be feasible. Cutting speeds in aluminum at up to at least 28,000 sfpm have already been demonstrated successfully.

4-5.3 Specific Machine Tool Configurations Used in Study

Projected panel machining times and monthly production rates were determined for the following specific gantry type machine tool configurations. (The columns of the tables showing the results are arranged in this order throughout the report):

- a) Present conventional gantry type mill with one 20 hp, 3,600 rpm spindle, and 200 ipm gantry feed (Figure 4-1).
- b) Present conventional gantry type mill retrofitted with new HSM 100 hp, 2,600 rpm conventional spindle(s) (1 or 2) and 200 ipm gantry feed (Figure 4-1).
- c) Present conventional gantry type mill retrofitted with new HSM 100 hp, 12,000 rpm spindle(s) (1 or 2) and 200 ipm gantry feed (Figure 4-1).
- d) New Conventional gantry type mill with horizontal 100 hp, 3,600 rpm and vertical 150 hp, 3,600 rpm spindle combination(s) (2, 4 or 8 spindles) and 300 ipm gantry feed for one panel width and 200 ipm gantry feed for two panel widths (This configuration is similar to Figures 4-1 and 4-3 but with both vertical and horizontal spindles).
- e) New conventional gantry type mill with vertical 150 hp, 3,600 rpm spindle (s) (1, 2 or 4) and 300 ipm gantry feed for one panel width and 200 ipm gantry feed for two panel width (Figures 4-1 and 4-3).
- f) New HSM gantry type mill with vertical 75 hp, 9,000 rpm spindle(s) (1, 2, or 4) and 600 ipm gantry feed for one panel width and 200 ipm for two panel widths (Figures 4-1 and 4-3).
- g) New HSM gantry type mill with vertical 100 hp, 12,000 rpm spindle(s) (1, 2, or 4) and 400 ipm gantry feed for one panel width and 200 ipm for two panel widths (Figures 4-1 and 403).
- h) New HSM gantry type mill with vertical 150 hp, 24,000 rpm spindle(s) (1, 2 or 4) and 1,000 ipm gantry feed for both one and two panel widths (Figures 4-1 and 403).
- i) New HSM gantry type mill (same as 8) except calculations are made using different roughing cutter.

Machining times and production rates were also calculated for configurations d) thru h) with two panel length tables. The lengthened tables were to provide loading and unloading capability without interrupting the machining process.

The outputs from the vertical panel machines (Figures 4-4 and 4-5) are expected to be comparable to the outputs attainable on the horizontal panel machines. However, development of the vertical panel machines has not progressed as far as for the horizontal machines and a column feed rate of 200 ipm was the apparent maximum.

4-5.4 Machining Parameters (Appendixes A and B)

Cutters

The study was based primarily on cutter sizes used for the present operation. where applicable (Section 4-1 and 4-4). The cutters used for roughing and finishing the pockets between the T-ribs were changed from the 5-1/4 inch diameter to 9 inches in most instances. For the combination horizontal and vertical spindle machines, a 14 inch diameter by 2.7 inch wide staggered tooth cutter with 8 teeth was used for roughing. This cutter was reportedly being used effectively on similar panels being machined at other facilities A 9 inch diameter cutter in the vertical spindle was used for the finishing.

Calculations were also made for roughing and finishing the pockets using a 5-1/4 inch cutter (as now used) on all of the machine configurations. The results are not shown in the report since in all instances the time was greater than when using the 9 inch diameter cutter.

Spindle Speeds

The maximum rpm available was used unless otherwise noted.

Horsepower Required

The metal removal rates are based on a full 100 percent of the rated horsepower of the spindle motors. The amount shown was calculated by dividing the cu in./min by a cutting efficiency factor of 4.0 cu in./min/hp (demonstrated in Task B and in other instances of HSM).

Chip Load

HSM research has defined optimum chip loads (chip per tooth) for milling aluminum¹. Chip loads of .007 inches for roughing and .003 inches for finishing were taken from these recommended ranges and maintained as constants throughout the study. Exceptions were the present operations and a few other instances as noted where machine capabilities were limiting.

Number of Layers

The number of layers in which the metal in the pockets between the ribs was rough machined was determined by computing the maximum cross-sectional area of metal removable based upon a cutting efficiency factor of 4.0 cu in/min/hp and the available horsepower. The maximum axial depth of cut equivalent for the full diameter (radial depth of cut) of the cutter was then calculated. This maximum depth per pass was then divided into the total roughing depth of 1.525 inches (1.75"-.100" finish cut - .125" panel thickness). The figure was adjusted to the next larger whole number and the 1.525 inch roughing depth was divided into equal depth layers each of which was considered to be the depth of cut (axial).

Number of Passes per Pocket

The number of passes per pocket was determined by multiplying the number of layers by the number of passes per layer.

Depth of Cut (Axial)

(See Number of Layers)

Depth of Cut (Radial)

The full diameter of the cutter was used as the radial depth of cut for the vertical spindles. For the horizontal spindles the radial depth was calculated depending on the number of passes required to achieve the depth of the pocket.

Table (Gantry) Feed Used

This value was calculated in each instance based on constant chip load, rpm, and number of teeth in the cutter. The calculated value was used unless the maximum capability of the machine was limiting. In such instances the exception was noted.

Cu In./Min - Metal Removal Rate

The metal removal rate value in cubic inches per minute was based on the maximum rate used and the full width of the cutter.

¹J. McGee et al, "Manufacturing Methods for High Speed Machining of Aluminum," Final Technical Report, Vought Corporation contract No. DAAK-40-76-C-1329; submitted to U. S. Army Missile Research and Development Command, February 1, 1978.

Cutting Speed

This value was computed as the peripheral speed of the cutter at the given rpm expressed in surface feet per minute (sfpm).

4-5.5 Chip Cutting Time for Each Machining Operation

Chip cutting time was considered to be only that time during which the revolving cutter is actually engaging the workpiece. Detailed calculations for each of the separate machining operations and for each machine configuration considered are shown in Appendixes A and B. The cutter paths used are considered reasonable but not necessarily optimum. Optimization of the cutters and other parameters should yield even shorter cutting times. A summary of these individual machining operation times and a composite total is provided in Table 4-1.

The data (Table 4-1) show that as rpm is increased the total chip cutting time is decreased. Theoretically, if a table feed of 1,344 ipm had been available for the 150 hp, 24,000 rpm spindle machine, an additional .359 hours (21.54 minutes) per panel would have been saved.

The values shown in Table 4-1 (and Appendixes A and B) are based upon one spindle operation. These one spindle values are expanded to the two and four spindle levels by dividing the one spindle chip cutting time by two and by four, respectively.

4-5.6 Total Machining Time

Machining time was computed to be the sum of chip cutting time plus between pass cutter positioning time. The time allowed for positioning was adjusted according to the maximum gantry feed available for the particular machine tool configuration. Tool changes, operator break, and down times were not included.

Table 4-2 shows the estimated machining time per spindle for one, two, and four spindle machines. This separation was required because the gantry feed of the four spindle machines is slower.

Table 4-1. Summary of Estimated Chip Cutting Time (Hours) Per Panel
(Based on One Spindle)

PRESENT	RETROFIT		MACHINE TOOL CONFIGURATIONS					
	CONV.	HSM	CONVENTIONAL			HIGH SPEED MACHINING		
	Existing	Existing	Horiz. for Rough	Vert. for Rough	Vertical Spindle 75 hp	Vertical Spindle 100 hp	Vertical Spindle 150 hp	Vertical Spindle 150 hp
Existing					3600 rpm	3600 rpm	3600 rpm	24000 rpm
20 hp 3600 rpm	100 hp 3600 rpm	100 hp 12000 rpm	100@150 hp 3600 rpm	100@150 hp 3600 rpm	9000 rpm	12000 rpm	12000 rpm	24000 rpm
Cutters+ PARAMETERS	5 ¹ / ₂ " Rough 6 Finish	9" Rough & Finish	14" Rough 9" Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	2" Rough 9" Finish
MACHINING OPERATIONS								
Mill Top of T's	4.032	.547	.239*	.547	.547	.225	.167	.084
Rough Mill Pockets	32.256	1.813	1.813*	2.766	1.295	2.368	1.716	1.220**
Finish Mill Pockets (.100")	8.064	.593	.259*	.593	.593	.243	.181	.084
Mill T-Ribs	4.838	4.493	1.382	4.493	4.493	1.728	1.382	.691
Mill Edge of T's and Radius	2.419	2.246	.691	2.246	2.246	.864	.691	.346
Mill Taper on T Ends	.040	.040	.040	.040	.040	.040	.040	.040
Mill Periphery	.256	.238	.073	.238	.238	.092	.073	.037
Total Chip Cutting Time	51.905	9.970	4.497*	10.923	9.452	5.560	4.250	2.502**
								2.708

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*Limited by 200 ipm table travel.
**Limited by 1000 ipm table travel.

Table 4-2. Summary of Estimated Machining Time Per Panel
(Chip Cutting Time Plus Cutter Positioning Time)

MACHINE TOOL CONFIGURATIONS									
PRESENT	RETROFIT		CONVENTIONAL		HIGH SPEED MACHINING (HSM)		NEW		MACHINE TOOL CONFIGURATIONS
	CONV.	HSM!	Horiz. for Rough Vert. for Finish	Vertical Spindle 150 hp 3600 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm	
Existing	Existing	Existing	for Rough Vert. for Finish	Vertical Spindle 100&150 hp 3600 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm	
20 hp 3600 rpm	100 hp 3600 rpm	100 hp 12000 rpm							
Cutters+ PARAMETERS	5½" Rough & Finish	9" Rough & Finish	14" Rough 9" Finish	14" Rough 9" Finish	9" Rough 6 Finish	9" Rough 6 Finish	9" Rough & Finish	2" Rough 9" Finish	
Total Chip Cutting Time (Hours)	51.905	9.970	4.497	10.923	9.452	5.560	4.250	2.502	2.708
Positioning Time (Hours) Per Pass									
- One or Two Spindle Machine (Hours)	.0025	.0025		.00167	.00083		.00125	.0005	.0005
- Four Spindle Machine (Hours)	-	-		.0025	.0025		.0025	.0005	.0005
# of Passes	225	209	209	266	183	417	404 (209)	416	303
Total Cutter Positioning Time									
- One or Two Spindle Machine (Hours)	.563	.523	.523	.444	.306	.346	.505	.208	.152
- Four Spindle Machine (Hours)	-	-	-	.665	.458	1.043	.523	.208	.152
Total Machining Time (Hours)	52.468	10.493	5.020	11.367	9.758	5.906	4.755	2.710	2.860
- One or Two Spindle Machine (Hours)	-	-	-	11.588	9.910	6.603	5.020	2.710	2.860

4-5.7 Total Floor-to-Floor Machining Time and Monthly Panel Machining Capacity

Total floor-to-floor time was determined to be the machining time plus operator break, fatigue, and personal time plus panel loading and unloading time. The operator break, fatigue, and personal time was estimated at 20 percent of machining time. Panel loading and unloading time was included at the reported present rate of 3.0 hours for the one panel width machines and an estimated 4.5 hours (2.25 hours per panel) for the two panel width machines. As the loading and unloading times were considered to be different for one and two panel width machines and also for one and two panel length machines, separate tables (C-1 through C-6) are shown in Appendix C for each of these categories. The monthly panel machining capacity was computed by dividing the total floor-to-floor time into the 325.5 hours per month total production time available on a two shift basis. This 325.5 hours per month was determined as follows:

$$\begin{aligned} \text{Day shift: } 21 \text{ days} \times 8 \text{ hours/day} &= 168 \text{ hours} \\ \text{Swing shift: } 21 \text{ days} \times 7.5 \text{ hours/day} &= 157.5 \text{ hours} \\ \text{Total for two shifts} &= 325.5 \text{ hours} \end{aligned}$$

Operator break, fatigue, and personal time have already been included in the floor-to-floor time. However, maintenance and other down times have not been allowed for.

A summary of total floor-to-floor machining time and monthly panel machining capacity is given in Tables 4-3 and 4-4.

It is noteable that in all instances the estimated monthly panel capacity increases as rpm is increased unless the capacity is limited by the load and unload time. It is also of interest that the estimated monthly panel capacity increases for each number of spindles when the table is lengthened to allow loading and unloading during machining.

4-6 ECONOMIC TRADE-OFF ANALYSIS

An economic trade-off analysis is a very important aspect of the High-Speed Machining of Space Shuttle External Tank Panels study. Even though the HSM process might be shown to produce panels faster, if the cost for producing the panels by this means is too high the change could not be justified. The approach taken to determine the estimated costs involved in machining panels using each of the 41 machine tool configurations included in the study was to assess both the machine investment cost and the machining time or labor figure. Some additional manufacturing costs, such as panel premachining which were considered to be essentially the same for each of the configurations, were not included in

Table 4-3. Summary of Total Floor-to-Floor Machining Time, Per Panel,
and Monthly Panel Machining Capacity

One Panel Length Machine

MACHINE TOOL CONFIGURATIONS									
RETROFIT		CONVENTIONAL		HIGH SPEED MACHINING (HSM)				NEW	
PRESENT	CONV.	HSM		Horiz. for Rough Vert. for Finish	Vertical Spindle 150 hp 3600 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm
Existing	Existing	Existing							
20 hp 3600 rpm	100 hp 3600 rpm	100 hp 12000 rpm							
Cutters+ & Finish	9" Rough & Finish	9" Rough & Finish		14" Rough 9" Finish	9" Rough 9" Finish	9" Rough 6 Finish	9" Rough & Finish	9" Rough & Finish	9" Rough 9" Finish
<u>One Spindle</u>									
Total Floor-to-Floor Time (hours)	65.962	15.592	9.024		16.640	14.710	10.087	8.706	6.252
Monthly Capacity 2 shifts/80% Cap.	3.9	16.7	28.9		15.6	17.7	25.8	29.9	41.7
2 shifts/100% cap.	4.9	19.5	36.1		19.6	22.1	32.3	37.4	52.1
<u>Two Spindle</u>									
Total Floor-to-Floor Time (hours)	-	9.296	6.012		9.821	8.855	6.544	5.854	4.626
Monthly Capacity 2 shifts/80% Eff.	-	28.0	43.4		26.5	29.4	39.8	44.5	56.3
2 shifts/100% Eff.	-	35.0	54.1		33.1	36.8	49.7	55.6	70.4
<u>Four Spindle</u>									
Total Floor-to-Floor Time (hours)	-	-	-		5.726	5.224	4.196	3.743	3.064
Monthly Capacity 2 shifts/80% Eff.	-	-	-		45.5	49.8	62.1	69.6	85.0
2 shifts/100% Eff.	-	-	-		56.8	62.3	77.6	87.0	106.2

Table 4-4. Summary of Total Floor-to-Floor Machining Time, Per Panel, and Monthly Panel Machining Capacity

Two Panel Length Machine									
MACHINE TOOL CONFIGURATIONS									
RETROFIT		CONVENTIONAL		HIGH SPEED MACHINING (HSM)				NEW	
(XXX) value if not limited by equipment	PRESENT	CONV.	HSN	Horiz. for Rough Vert. for Finish	Vertical Spindle 150 hp 3600 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm
Existing 20 hp 3600 rpm	Existing 100 hp 12000 rpm	Existing 100 hp 12000 rpm	Existing 100 hp 3600 rpm	14" Rough 9" Finish	9" Rough 6" Finish	9" Rough 6" Finish	9" Rough & Finish	9" Rough & Finish	9" Finish
Cutters→ 5½" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	13.640	11.710	7.087	5.706	3.252	3.432
<u>One Spindle</u>									
Total Floor-to-Floor Time (Hours)	65.962	-	-						
Monthly Capacity 2 shifts/80% Eff. 2 shifts/100% Eff.	3.9	-	-	19.1	22.2	36.7	45.6	80.1	75.9
	4.9	-	-	23.9	27.8	45.9	57.0	100.1	94.8
<u>Two Spindle</u>									
Total Floor-to-Floor Time (Hours)	-	-	-	6.821	5.855	3.544 (2.854)	3.000 (2.854)	3.000 (1.626)	3.000 (1.716)
Monthly Capacity 2 shifts/80% Eff. 2 shifts/100% Eff.	-	-	-			73.5	86.8	86.6	86.8
	-	-	-	38.2	44.5		(91.2)	(160.1)	(151.7)
<u>Four Spindles</u>									
Total Floor-to-Floor Time (Hours)	-	-	-	3.476	2.974	2.250 (1.946)	2.250 (1.493)	2.250 (.814)	2.250 (.858)
Monthly Capacity 2 shifts/80% Eff. 2 shifts/100% Eff.	-	-	-						
	-	-	-	74.9	87.6	115.7 (133.8)	115.7 (174.4)	115.7 (319.9)	115.7 (303.5)
	-	-	-	93.6	109.4	144.7 (167.3)	144.7 (218.0)	144.7 (399.9)	144.7 (379.4)

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the comparison study.

The production requirements were specified to be 64 panels per month for 84 months (5,376 panels) starting in 1985. The costs were computed both per panel and per the total 5,376 panels.

4-6.1 Labor Costs Per Panel and Per 5,376 Panels

The labor cost per panel for each of the 41 configurations was determined by multiplying the total floor-to-floor machining time per panel by a constant labor rate. An appropriate labor charge for the type of work and equipment involved was estimated at \$60 per hour. These labor costs are shown in Table D-1 and D-2 of Appendix D. Also shown are the labor costs projected for the total 5,376 panels if machined by each of the configurations.

4-6.2 Machine Investment Costs Per Panel and Per 5,376 Panels

The costs of the machines were estimated by various machine tool builders. A degree of interpolation was involved in costing certain specific machine tool configurations. In the case of the retrofit machines, no value for the present machine was allowed; only additional investment costs were figured. The primary costs for the retrofits were for the HSM spindle motor systems.

The cost of the vacuum chuck system was, in some instances, included in the cost of the machine. The estimates for installation and debug and test were determined from inputs from the machine tool builders and from Lockheed personnel experienced in the area (Tables E-1 through E-6, Appendix E).

4-6.3 Combined Machine Investment Plus Labor Costs Per Panel and Per 5,376 Panels

The machine investment costs and the labor costs for the various machine tool configurations are combined in Tables F-1 through F-6 of Appendix F. Both costs per panel and per the total of 5,376 panels are shown. Summary comparisons of these combined costs per panel are given in Table 4-5 and total costs for all 5,376 panels are given in Table 4-6.

Of interest is the indication that, for the new machines, the combined cost per panel goes down as the rpm of the spindle motors goes up.

Table 4-5. Summary of Combined Total Machine Investment Plus Labor Cost (\$) Per Panel

		MACHINE TOOL CONFIGURATIONS					
		NEW			HIGH SPEED MACHINING		
RETROFIT		CONVENTIONAL		Vertical Spindle 100 hp 12000 rpm		Vertical Spindle 100 hp 24000 rpm	
PRESENT	HSM	Vert. for Rough Hori. for Finish	Vert. Spindle 150 hp 3600 rpm	Vertical Spindle 150 hp 9000 rpm	Vertical Spindle 150 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm
(XXX) values not limited by load/unload times							
Existing	Existing	Vert. for Rough Hori. for Finish	Vert. Spindle 150 hp 3600 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 100 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm
20 hp 3600 rpm	100 hp 3600 rpm	100 hp 3600 rpm	100 hp 3600 rpm	100 hp 3600 rpm	100 hp 12000 rpm	100 hp 24000 rpm	150 hp 24000 rpm
20 hp 3600 rpm	100 hp 3600 rpm	100 hp 3600 rpm	100 hp 3600 rpm	100 hp 9000 rpm	100 hp 12000 rpm	100 hp 24000 rpm	150 hp 24000 rpm
Cutters+ PARAMETERS	5/8" Rough & Finish	9" Rough & Finish	14" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish
One Spindle							
One Panel Length Table	3,958	945	586	1,409	1,266	923	859
Two Panel Length Table	-	-	-	1,310	1,167	1,972	741
Two Spindle							
One Panel Length Table	-	577	437	1,056	942	739	753
Two Panel Length Table	-	-	-	957	844	622	645
Four Spindle							
One Panel Length Table	-	-	-	1,013	852	791	783
Two Panel Length Table	-	-	-	991	830	787	806

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Table 4-6. Summary of Combined Total Machine Investment Plus Labor Cost (\$)
Per 5,376 Panels

		MACHINE TOOL CONFIGURATIONS					
		NEW			HIGH SPEED MACHINING (HSM)		
		RETROFIT		CONVENTIONAL			
PRESENT	CONV.	HSM					
Existing	Existing	Existing	Horiz. for Rough Vert. for Finish	Vertical Spindle 150 hp 3600 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 150 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm
Cutters+ Spindle	20 hp 3600 rpm	100 hp 3600 rpm	100 hp 3600 rpm	100 hp 3600 rpm	100 hp 9000 rpm	100 hp 12000 rpm	100 hp 24000 rpm
PARAMETERS	5 ^{1/2} " Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish
<u>One Spindle</u>							
One Panel Length Table	21,278K	5,082K	3,150K	7,575K	6,807K	4,962K	3,501K
Two Panel Length Table	-	-	-	7,043K	6,274K	4,330K	2,694K
<u>Two Spindle</u>							
One Panel Length Table	-	3,102K	2,352K	5,677K	5,066K	3,974K	4,048K
Two Panel Length Table	-	-	-	5,147K	4,535K	3,343K	3,466K (3,417K)
<u>Four Spindle</u>							
One Panel Length Table	-	-	-	5,448K	4,582K	4,252K	4,208K
Two Panel Length Table	-	-	-	5,331K	4,464K	(4,136K)	4,333K (4,019K)

4-6.4 Comparison of Monthly Panel Machining Capacities of Various Machine Tool Configurations

Table 4-7 shows the projected monthly panel machining capacities of the 41 different machine tool configurations. Details are compiled in Appendix C. The information in Table 4-7 is based on a 100 percent efficiency factor after operator break, fatigue, and personal time have been allowed.

- Additional time should be allocated for maintenance (commonly 10 percent or higher for conventional numerical control machining centers) and other miscellaneous reasons. Furthermore, in this study no time has been allowed for secondary machining operations such as drilling and tapping holes while the part is still mounted on the machine. A realistic estimate of actual productive machine time for the milling operation would be 80 percent. Table 4-8 shows the projected monthly panel machining capacities of the 41 machine tool configurations at this 80 percent level.

4-6.5 Selection of Best Alternative Machine Configurations

Criteria used for selection were:

- a) The machine must meet or exceed the production requirement of 64 panels per month (using the 80 percent efficiency level).
- b) The panels must be produced at the least reasonable combined total machine investment plus labor cost.
- c) The machine tool configuration must be reasonably well proven.

Table 4-9 shows the 15 machine tool configurations selected which are expected to meet or surpass the 64 panel per month production requirement. In addition to the monthly panel capacity, the combined total machine investment and labor costs are shown. Eight of the 15 configurations involve the 150 hp, 24,000 rpm spindle which at this time is felt to need further proofing before it can be recommended. Table 4-10 shows the machine tool configurations selected for each of the three following major categories.

a) Retrofit HSM

Two present gantry type milling machines (each retrofitted with two 100 hp, 12,000 rpm vertical spindles) show a combined projected panel machining capacity of 86.6 panels per month at an estimated labor plus additional investment cost for the retrofit of \$4,704,000 or \$875 per panel.

Table 4-7. Estimated Panel Machining Capacities of 41 Machine Tool Configurations -Panels/Month

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		100 Percent Efficiency Level					
		Machine Tool Configurations					
(XXX) values not limited by load/unload times	PRESENT	RETROFIT		CONVENTIONAL		HIGH SPEED MACHINING (HSM)	
		CONV.	HSM	Horiz. for Rough Vert. for Finish	Vertical Spindle 150 hp 3600 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 150 hp 24000 rpm
Existing	Existing	100 hp 3600 rpm	100 hp 12000 rpm	Vertical Spindle 150 hp 3600 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm
20 hp 3600 rpm							
Cutters+ 5½" Round & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	14" Rough 9" Finish	9" Rough 6 Finish	9" Rough 6 Finish	9" Rough 9" Finish
PARAMETERS							
One Spindle							
One Panel Length	4.9	19.5	36.1	19.6	22.1	32.3	37.4
Table							
Two Panel Length	-	-	-	23.9	27.8	45.9	57.0
Two Spindle							
One Panel Length	-	35.0	54.1	33.1	36.8	49.7	55.6
Table							
Two Panel Length	-	-	-	47.7	55.6	91.8	108.5
Four Spindle							
One Panel Length	-	-	-	56.8	62.3	77.6	87.0
Table							
Two Panel Length	-	-	-	93.6	109.4	144.7	144.7
Table						(167.3)	(399.9)

Table 4-8. Estimated Monthly Panel Machining Capacities of 41 Machine
Tool Configurations (Number of Panels)

(Two Shift Operation)
80 Percent Efficiency Level

PRESENT	RETROFIT		MACHINE TOOL CONFIGURATIONS					
	CONV.	HSM	CONVENTIONAL		HIGH SPEED MACHINING (HSM)		NEW	
Existing	Existing	Existing	Horiz. for Rough	Vertical Spindle	Vertical Spindle	Vertical Spindle	Vertical Spindle	Vertical Spindle
20 hp 3600 rpm	100 hp 3600 rpm	100 hp 12000 rpm	Vert. for Finish	150 hp 3600 rpm	150 hp 9000 rpm	100 hp 12000 rpm	150 hp 24000 rpm	150 hp 24000 rpm
CUTTERS*	5½" Rough & Finish	9" Rough & Finish	14" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish
PARAMETERS								
<u>One Spindle</u>								
One Panel Length Table	3.9	16.7	28.9	15.6	17.7	25.8	29.9	41.7
Two Panel Length Table	-	-	-	19.1	22.2	36.7	45.6	80.1
<u>Two Spindle</u>								
One Panel Length Table	-	28.0	43.3	26.5	29.6	39.8	44.5	56.3
Two Panel Length Table	-	-	-	38.2	44.5	73.5	86.8 (91.2)	86.8 (160.1)
<u>Four Spindle</u>								
One Panel Length Table	-	-	-	45.5	49.8	62.1	69.6	85.0
Two Panel Length Table	-	-	-	74.9	87.6	115.7	115.7 (133.8)*	115.7 (319.9)*

(XXX) values not limited by load/unload times

*(XXX) values not limited by gantry speed

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Table 4-9. Estimated Panel Machining Capacities and Combined Costs (\$) of 15 Machine Tool Configurations Meeting 64 Panel Per Month Requirements

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		MACHINE TOOL CONFIGURATIONS						80 Percent Efficiency Level	
		RETROFIT			NEW			HIGH SPEED MACHINING (HSM)	
PRESENT	CONV.	CONVENTIONAL		HORIZ.	VERTICAL		VERTICAL SPINDLE 150 HP 24000 RPM	VERTICAL SPINDLE 150 HP 24000 RPM	VERTICAL SPINDLE 150 HP 24000 RPM
		for Rough	for Finish		Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm			
Existing	Existing	Vert. for Rough	Vert. for Finish	Vertical Spindle 150 hp 3600 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm
20 hp 3600 rpm	100 hp 3600 rpm	100 hp 3600 rpm	100 hp 3600 rpm	100 hp 3600 rpm	100 hp 3600 rpm	100 hp 3600 rpm	100 hp 3600 rpm	100 hp 3600 rpm	100 hp 3600 rpm
CUTTERS+	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	14" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish
PARAMETERS									
One Spindle									
One Panel Length Table					Two Panel Length Table				
Two Spindle									
One Panel Length Table					Two Panel Length Table				
Four Spindle									
One Panel Length Table					Two Panel Length Table				

Table 4-10. Recommended Machine Tool Configurations vs Total Cost and Cost Per Panel.

MACHINE TOOL CONFIGURATIONS								
PARAMETERS	RETROFIT		CONVENTIONAL		HIGH SPEED MACHINING (HSM)			
	PRESENT	CONV.	HSM	Horiz. for Rough	Vertical Spindle 100 & 150 hp	Vertical Spindle 75 hp	Vertical Spindle 100 hp	
Cutters→	Existing 20 hp 3600 rpm	Existing 100 hp 3600 rpm	Existing 100 hp 12000 rpm	Vertical Spindle 100 & 150 hp 3600 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm	
Two Spindle	5½" Rough & Finish	9" Rough & Finish	9" Rough & Finish	14" Rough & Finish	9" Rough & Finish	9" Rough & Finish	2" Rough & Finish	
One Panel Length Table	BEST RETROFIT (2 Machines)		86.6* \$4,704K (@\$875)		73.5* \$3,343K (@\$622)		86.8* \$3,466K (@\$645)	
Two Panel Length Table								
Four Spindle								
One Panel Length Table							87.6* \$4,464K (@\$830)	
Two Panel Length Table							115.7* \$4,091K (@\$761)	

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It is assumed that two saddles for mounting the spindles will be available on each machine and that the new Allen Bradley #7320 controls recently installed on the machine are capable of controlling the two spindles simultaneously as reported.

b) New Conventional

The best choice for a new conventional machine is a two panel wide, two panel long gantry type machine with four 150 hp, 3,600 rpm vertical spindles. This configuration is projected to have a panel machining capacity of 87.6 panels per month and have a combined total machine investment plus labor cost of \$4,464,000 or \$830 per panel.

c) High Speed Machines (HSM)

Five different machine configurations appear to meet all three of the selection criteria. Three configurations were identified involving the the least cost.

The two best choices are both gantry type milling machines with two spindles and a single width, double length table. The two 100 hp, 12000 rpm vertical spindle machine provides a capacity of 86.8 panels per month at an estimated combined machine investment plus labor cost of \$3,466,000 or \$645 per panel.

The other best choice machine has two 75 hp, 9,000 rpm vertical spindles, a capacity of 73.5 panels per month and is estimated to have a combined machine investment plus labor cost of \$3,343,000 or \$622 per panel.

The third lowest cost producing HSM configuration is the two panel wide, two panel long, gantry type machine with four 100 hp, 12,000 rpm vertical spindles. This machine has a projected panel machining capacity of 115.7 panels per month at an estimated combined investment plus labor cost of \$4,091,000 or \$761 per panel.

4-7 IMPLEMENTATION PLANS

Before a decision on retrofitting existing equipment or purchasing new is made, careful attention should be paid to several factors. Time should be allowed in the implementation schedule for a detailed vibration analysis of the present or other machine being considered for retrofitting. Estimated vendor delivery times should be confirmed since delivery schedules can vary noticeably with work load.

The following factors are involved and should be considered before the new or retrofit machine is fully ready for operation.

Retrofit Machine

The information in Figure 4-7 is provided as a guide for scheduling for a retrofit HSM system to be installed on the present machine.

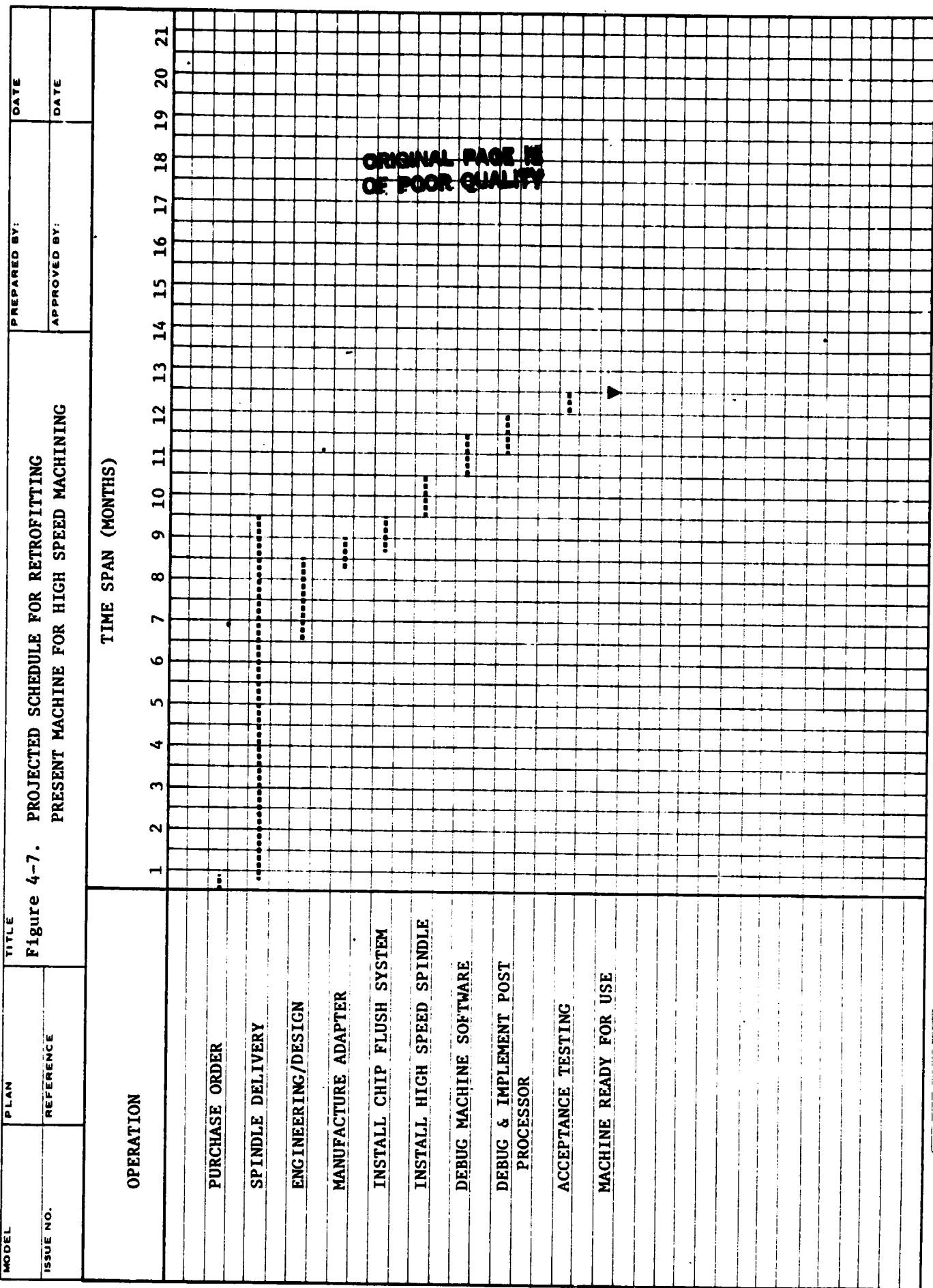
If a retrofit were to be made on this machine, schedule and budgetary provisions should also be provided for the updating of the electrical power supply and other items described in Section 5. The overall time from placing of order to full production readiness is expected to approach 12 months.

New Conventional or HSM Machine

A scheduling and planning guide is provided in Figure 4-8 to be used for the procurement, installation and readying of either a new conventional or HSM machine. The lead times estimated by the machine tool builders contacted were essentially the same for either type of machine. However, some variation should be expected from particular machine tool builders. The overall time from placing of order to full production readiness is expected to be at least 18 months.

Other Considerations

Other activities should take place concurrent with the installation. For example, specific cutter determination and NC programming should be established.

SCHEDULE PLAN

SCHEDULE PLAN

PROJECTED SCHEDULE FOR DELIVERY AND INSTALLATION OF NEW CONVENTIONAL OR HSM MACHINE

MODEL ISSUE NO.	PLAN REFERENCE	TITLE Figure 4-8. PROJECTED SCHEDULE FOR DELIVERY AND INSTALLATION OF NEW CONVENTIONAL OR HSM MACHINE	PREPARED BY:		DATE																		
			APPROVED BY:	DATE	APPROVED BY:	DATE																	
		OPERATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
		PURCHASE ORDER	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
		MACHINE DELIVERY	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
		FOUNDATION EXCAVATION	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
		FOUNDATION-STEEL, CONCRETE AND CURE	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
		MACHINE INSTALLATION	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
		DEBUG MACHINE SOFTWARE	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
		DEBUG & IMPLEMENT POST PROCESSOR
		ACCEPTANCE TESTING
		MACHINE READY FOR USE

TIME SPAN (MONTHS)

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FIGURE 4-8

SECTION 5

GENERAL DISCUSSION

5-1 COMPARISON WITH TASK B PROJECTED MACHINING TIMES

The 6.0 hours machining time projected from the 4 foot by 8 foot panel machined in Task B (Table 6-1 of the Task B report) for the Cincinnati Milacron 75 hp single spindle machine compares very closely to the 5.9 hours total machining time estimated for the 75 hp, 9,000 rpm spindle machine (Table 4-2). The 4.48 hours projected in Task B for the 100 hp, single spindle machine also compares very closely to the 4.75 hours total machining time determined in Task A. The estimates in Task A and Task B were similar even though computed using different procedures.

5-2 PRODUCTION RATE OF PRESENT MACHINE

The 3.9 panel per month baseline production rate of the present machine is relatively low and is obviously limited by the low (20 hp) spindle motor. A more realistic baseline might be 16.7 panels per month projected as obtainable with a retrofit 100 hp, 3,600 rpm spindle (Figure 4-8). The 3.9 panel per month baseline production rate was calculated using current parameters for metal removal and assuming the starting stock to be 1.75 inch thick solid plate.

5-3 RETROFIT OF PRESENT MACHINE

When considering conversion of the present gantry type mill to HSM, the following decision making criteria should be included.

- a. The current capital investment value of this machine was not included in this study. Only the additional retrofitting cost was considered.
- b. The machine is approximately 20 years old but has been recently rebuilt and a new control has been added.
- c. The present electrical power supply to the machine is reportedly capable of handling only 13 hp and will probably need to be replaced.
- d. The gantry should operate at 200 ipm. Reportedly it can be operated currently at a maximum of 150 ipm. This limitation would need to be remedied.
- e. Before a final decision to retrofit with large, powerful spindle motors is made, a detailed vibration analysis should be performed to insure a fully functional system. The presence of the current single 20 hp motor instead of two 100 hp motors (reportedly original equipment) may indicate problems of lack of rigidity and resulting vibrations.

f. A chip removal system should be defined and provided.

5-4 SELECTION OF GENERAL MACHINE TOOL CONFIGURATIONS

The best choice of the general machine configurations based on production capacity, labor cost, and machine investment cost is the two panel length, gantry type machine with two vertical spindles. Although the vertical panel machine concept has better chip removal characteristics, none of the machine tool builders contacted felt that it would be feasible to move the tall column required for an 11 foot wide panel at the feed rates desired for HSM.

The 100 hp, 12,000 rpm spindle is the best choice of spindle. The projected production capacity should be adequate and could be increased if the loading and unloading time were reduced.

The 150 hp, 24,000 rpm spindle coupled with the 1,000 ipm gantry feed is theoretically capable of considerably higher production rates than the lower rpm machines but the proposed designs need to be more fully proven. Furthermore, cutters are not yet available which would allow full utilization of machine potential.

The second choice of spindle is the well proven 75 hp, 9,000 rpm version. However, the monthly production capacity of this machine is somewhat lower than for the 100 hp, 12,000 rpm spindle.

Of the 41 machine configurations compared, 15 would be capable of meeting the capacity requirements of 64 panels per month at varying combined labor plus machine investment costs. However, eight of the 15 configurations involve the 150 hp, 24,000 rpm spindle which needs to be further proven.

5-5 CUTTERS

The study was based on the assumption that cutters are available (or shortly will be) which are capable of operating at the cutting speeds of interest. Availability was based on contacts with machine tool builders and cutter manufacturers. However, for the highest cutting speeds indicated (especially 56,549 sfpm) cutters are definitely not yet available.

5-6 CHIP REMOVAL

The volume of chips produced is in direct relationship to the machining metal removal rate. At the very high metal removal rates under study, the removal requirements for the chips becomes significant and dictates a need for mechanized systems for chip removal.

The most highly recommended chip removal method for the gantry type milling machines is by vacuum. The chips are collected from an inlet located at each cutter and conducted to a common disposal point where coolant is reclaimed. The cost of such a system is estimated to be from \$350,000 to \$400,000 per machine. The cost for a chip removal system has not been included in the machine investment cost figures in this study.

Section 6

CONCLUSIONS

6-1 MACHINE TOOL CONFIGURATIONS

Based on the required 64 panel per month production rate (for 5,376 panels), the following machine tool configurations, cost savings and production rates are projected:

- a. High Speed Machine (1) with (2) State-of-the-Art 75 hp High Speed Spindles.
 - o \$17,935,000 Cost savings
 - o 73.5 panels per month rate
- b. High Speed Machine (1) with (2) Advanced 100 hp High Speed Spindles
 - o \$17,812,000 Cost savings
 - o 86.6 panels per month rate
- c. New Conventional High-Capacity Machine (1) with (4) Conventional 150 hp Spindles
 - o \$16,814,000 cost savings
 - o 87.6 panels per month rate
- d. Retrofit for (2) Existing Machines each with (2) Advanced 100 hp High Speed Spindles
 - o \$16,574,000 cost savings
 - o 86.6 panels per month rate

6-2 PROVEN HSM EQUIPMENT

Using proven HSM equipment, production rates could be increased from a baseline of 3.9 panels per month to 73.5 panels per month. The equipment used would be a one panel wide, two panel long gantry type mill with two 75 hp, 9,000 rpm spindles. The combined labor plus machine investment cost would be reduced from \$3,958 to \$622 per panel. The total estimated savings of 5,376 panels would be \$17,935,000.

6-3 ADVANCED HSM EQUIPMENT

Advanced HSM equipment (not fully proven but at a high confidence level) would increase production rates from the current 3.9 panels per month to 86.6 panels per month. Equipment would be a one panel wide, two panel long gantry type machine with two 100 hp, 12,000 rpm vertical spindles. Labor plus machine investment cost would be reduced from a baseline of \$3,958 to \$645 per panel and estimated savings (on 5,376 panels) would be \$17,812,000.

6-4 MAXIMUM PANEL AND SPINDLES BENEFITS

A two panel wide, two panel long gantry type machine with four 75 hp or greater HSM vertical spindles, would increase production rates from 3.9 panels per month to 115.7 panels per month (limited by load and unload time). The combined labor plus machine investment cost would be reduced from a baseline of \$3,958 to \$769 per panel for four 75 hp, 9,000 rpm spindles and have a projected total savings of \$17,142,000 for 5,376 panels. A comparable reduction with four 100 hp, 12,000 rpm spindles would be from the baseline of \$3,958 to \$761 per panel at a projected total savings of \$17,187,000.

6-5 RETROFITTING WITH HSM SPINDLES

Production rates could be increased from 3.9 panels per month currently to an estimated 43.4 panels per month by retrofitting two 100 hp, 12,000 rpm HSM spindles on the present gantry type mill. Two machines thus converted would be needed to achieve the 64 panel per month production requirement. The projected combined labor plus additional retrofitting machine investment cost (two machine) would be reduced from baseline \$3,958 to \$875 per panel for a total savings of \$16,574,000 on 5,376 panels.

6-6 NEW CONVENTIONAL MACHINE

A new conventional machine could be used to increase production rates from 3.9 currently to 87.6 panels per month. This could be accomplished with a two panel wide, two panel long gantry type machine and four 150 hp, 3,600 rpm spindles. The projected combined labor plus machine investment cost would be reduced from baseline \$3,958 to \$830 per panel at a total estimated savings of \$16,814,000 on 5,376 panels.

6-7 DEVELOPMENT HSM SPINDLES AND 1,000 IPM FEEDS

Extremely high production rates were indicated through use of HSM with 150 hp, 24,000 rpm spindle machines with 1,000 ipm gantry feed. However, these machines (and cutters to utilize their full potential) are not sufficiently proven to be recommended in this study. The potential of such a machine however, indicates an \$18,106,000 cost savings (5,376 panels) for a four (4) spindle, two panel width, two panel length configuration. With unrestricted gantry speed and load/unload times, production rates of 320 panels per month were projected!

6-8 HORSEPOWER EFFECTS

Horsepower was the dominant factor regarding the metal removal rate during the rough machining operation regardless of rpm or cutting speed (sfpm).

6-9 DOMINANT FACTORS - METAL REMOVAL RATE

Rpm and gantry feed (ipm) were the dominant factors regarding the metal removal rate during the finishing operations. The production capacity of the machines increased as rpm and gantry feed were increased.

6-10 ADDED TABLE LENGTH

The addition of the second table length to allow machining to continue during loading and unloading, increased the production capacity and decreased the cost per panel in all instances.

6-11 LOAD/UNLOAD TIME

Loading and unloading time became a limiting factor at the high production capacities even for the two panel length machines.

6-12 HORIZONTAL VS VERTICAL SPINDLES

The machines with horizontal spindles for rough machining and vertical spindles for finish machining showed a lower production capacity and higher cost per panel than for comparable machines with vertical spindles only.

6-13 PANEL MOUNTING

Machines with vertical mounting of panels would appear to be best suited for convenient chip removal. At the current state of development, however, travel rates for the moveable columns are not competitive with the gantry type machines.

6-14 CHIP REMOVAL

Chip removal is a very important consideration. Currently, the most highly recommended system for large horizontal panels utilizes vacuum removal techniques that are proven and in use on other applications and that can handle without problem the large chip volumes typical of hsm.

APPENDIX A

MACHINING OPERATION TIME

- A-1 Rough Mill Pockets
- A-2 Finish Mill Bottom of Pockets
- A-3 Mill T-Ribs
- A-4 Mill Edge of T's and Radii

Table A-1. Determination of Machining Operation Time:
Rough Mill Pockets

(xxx) values limited by travel feed restrictions

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		MACHINE TOOL CONFIGURATIONS					
		NEW			HIGH SPEED MACHINING		
		RETROFIT		CONVENTIONAL			
PRESENT	CONV.	CONV.	HSM	CONV.	HSM	Vertical Spindle	Vertical Spindle
Existing	Existing	Existing	Existing	Horizontal for Rough	Vertical for Rough	Vertical Spindle	Vertical Spindle
20 hp 3600 rpm	100 hp 3600 rpm	100 hp 12000 rpm	100 hp 12000 rpm	Vert. for Finish 100-150 hp 3600 rpm	Vert. for Finish 150 hp 3600 rpm	150 hp 9,000 rpm	150 hp 24000 rpm
PARAMETERS	Cutters	5½" Rough & Finish	9" Rough & Finish	14" Rough & Finish	9" Rough & Finish	9" Rough & Finish	2" Rough & Finish
Cutter Diameter (in)	5-½	9	9	14	9	9	9
No. of Teeth	4	8	8	8	8	8	8
Chip Load (in)	.0008	.007	.002	.007	.007	.007	(.005)
No. of Layers	4	7	7	3	5	23	23
No. of Passes per Pocket	8	7	7	12	5	23	23
Depth of Cut (axial) (in)	.475 max	.218	.218	2.8 (Max.)	2.8 max.	.066	.066
Depth of Cut (radial) (in)	5.25	9	9	.508	9	9	9
Cross-Section/Pass (sq. in.)	2.494	1.962	1.962	1.422	2.745	.594	.624
Table Feed Used (ipm)	12	200 max	200 max	202	202	500	636
Cu. In./Min.	30	392	392	549	297	397	597
Horsepower Required max	13	98.1	98.1	71.8	137.0	74.3	99.2
Cutting Speed (sfpm)	4,948	8,482	28,274	13,195 8,482	8,482	21,206	28,274
Time Required (hrs)	32.256	1.813	2.766	1.295	2.368	1.716	1.4220

Table A-2. Determination of Machining Operation Time: Finish Mill Bottom of Pockets
 (9" Diameter Cutter, .100" Deep Except "Present" at CPC)

(Based on One Spindle)

PRESENT	MACHINE TOOL CONFIGURATIONS									
	RETROFIT			CONVENTIONAL			HIGH SPEED MACHINING (HSM)			
	CONV.	HSM		Horiz. for Rough	Vert. for Rough	Vertical Spindle 150 hp 3600 rpm	Vertical Spindle 100 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm
Existing 20 hp 3600 rpm	Existing 100 hp 3600 rpm	Existing 100 hp 12000 rpm		Vert. for Rough 100&150 hp 3600 rpm	Vertical Spindle 150 hp 3600 rpm					
Cutters+ 5½" Rough & Finish	9" Rough & Finish	9" Rough & Finish		14" Rough 9" Finish	9" Rough 9" Finish					
Cutter Dia. (In.) 5-1/4	9	9		9	9					
No. of Teeth 4	8	8		8	8					
Chip Load .0008	.003	.002*		.003	.003					
No. of Layers 1	1	1		1	1					
Total Passes/Pocket 2	1	1		1	1					
Depth of Cut (Axial) 5.25	.100	.100		.100	.100					
Depth of Cut (Radial) .100	9	9		9	9					
Cross-Section/Pass .525	.900	.900		.900	.900					
Table Feed Used 12	86	200*		86	86					
Cu.in./min. 6.3	77	180*		77	77					
Horsepower Required 1.6	19.4	45*		19.4	19.4					
Cutting Speed (sfpm) 4,948	8,482	28,274		8,482	8,482					
Hours Required 8.064	.593	.259*		.593	.593					

A-3

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*Reduced due to table feed limitation of 200 ipm.

Table A-3. Determination of Machining Operation Time: Mill T-Ribs
(Based on One Spindle)

PRESENT	RETROFIT		MACHINE TOOL CONFIGURATIONS					
	CONV.		HS!		CONVENTIONAL		HIGH SPEED MACHINING	
	Existing	Existing	Horiz.	for Rough Vert. Finish	Vertical Spindle 150 hp 3600 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm
Existing 20 hp 3600 rpm	100 hp 3600 rpm	100 hp 12000 rpm	100&150 hp 3600 rpm	14" Rough 9" Finish	9" Rough 9" Finish	9" Rough 9" Finish	9" Rough & Finish	9" Rough & Finish
Cutters+ 5 $\frac{1}{4}$ " Rough & Finish	.0019	.003	.003	.003	.003	.003	.003	.003
Cutter Diameter (In)	4	4	4	4	4	4	4	4
No. of Teeth	6	4	4	4	4	4	4	4
Chip Load (in.)	2	2	2	2	2	2	2	2
No. of Layers	2	2	2	2	2	2	2	2
Total # of passes/ Rib	4	4	4	4	4	4	4	4
Depth of Cut (axial) (In)	.725	.725	.725	.725	.725	.725	.725	.725
Depth of Cut (Radial) (In)	.575	.575	.575	.575	.575	.575	.575	.575
Cross - Section/Pass (sq. in.)	.417	.417	.417	.417	.417	.417	.417	.417
Table Feed Used (ipm)	40	43	44	43	43	108	144	288
Cu. In./Minute	17	18	60	18	18	4.5	60	120
Horsepower Required	4.3	4.5	15.0	4.5	4.5	11.3	15.0	30.0
Cutting Speed (sfpm)	3,770	3,770	12,566	3,770	3,770	9,425	12,566	25,133
Hours Required	4.493	4.493	1.382	4.493	4.493	1.728	1.382	.691

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Table A-4. Determination of Machining Operation Time: Mill Edge of T's and Radii
(Based on One Spindle)

*Assumed Value	PARAMETERS	MACHINE TOOL CONFIGURATIONS							
		NEW				HIGH SPEED MACHINING			
		RETROFIT		CONV.		CONVENTIONAL			
PRESENT		Existing	Existing	Vert. for Rough	Vertical Spindle	Vertical Spindle	Vertical Spindle	Vertical Spindle	Vertical Spindle
Existing				for Finish	150 hp	150 hp	100 hp	150 hp	150 hp
20 hp		100 hp	100 hp	150 hp	3600 rpm	3600 rpm	3600 rpm	3600 rpm	3600 rpm
3600 rpm		3600 rpm	12000 rpm	3600 rpm	1000 rpm	1000 rpm	9000 rpm	12000 rpm	9000 rpm
5 ¹ / ₂ " Cutters+	5 ¹ / ₂ " Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	14" Rough & Finish	14" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish
Cutter Diameter (in)	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
# of Teeth	4*	4	4	4	4	4	4	4	4
chip load (in)	.0028	.003	.003	.003	.003	.003	.003	.003	.003
No. of Layers	1	1	1	1	1	1	1	1	1
Total # of Passes / Rib	2	2	2	2	2	2	2	2	2
Depth of cut (Axial)	1.125	1.125	1.125	1.125	1.125	1.125	1.125	1.125	1.125
Depth of Cut (Radial) (in)	.296	.296	.296	.296	.296	.296	.296	.296	.296
Cross - Section/Pass (sq. in.)	.333	.333	.333	.333	.333	.333	.333	.333	.333
Table Feed Used (ipm)	40	4.3	14.4	4.3	4.3	10.8	14.4	28.8	28.8
Cu. In./Min.	13	14	48	14	14	36	48	96	96
Horsepower Required	3.3	3.5	12.0	3.5	3.5	9.0	12.0	24.0	24.0
Cutting Speed (sfpm)	2,356	7,854	2,356	2,356	5,891	7,854	15,708	15,708	15,708
Time Required	2.419	2.246	.691	2.246	2.246	.864	.691	.346	.346

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APPENDIX B

MACHINE RUN CALCULATIONS

- B-1 Present Method - 20 HP, 3600 RPM**
- B-2 9 inch Cutter 8 Teeth, Retrofit 100 HP, 3600 RPM, 200 IPM**
- B-3 9 inch Cutter 8 Teeth, Retrofit 100 HP, 12000 RPM, 200 IPM**
- B-4 14 inch Cutter (Roughing), 9 inch Cutter (Finishing)
100 HP and 150 HP**
- B-5 9 inch Cutter 8 Teeth, 150 HP, 3600 RPM**
- B-6 9 inch Cutter 8 Teeth, 75 HP, 9000 RPM**
- B-7 9 inch Cutter 8 Teeth, 100 HP, 12000 RPM**
- B-8 9 inch Cutter 8 Teeth, 150 HP, 24000 RPM**

Table B-1 Present Method — 20HP (13.2-TU), 3600 RPM

MACHINE RUN CALCULATIONS

NOTE: $a + b = c \times d \times e = f$

TOTAL MACHINE RUN -
(Transfer to front page)

Table 3-2 9" Cutter, 8 Teeth, Retrofit 100HP, 2300 RPM, 2002MM

MACHINE RUN CALCULATIONS

NOTE: $a + b = c \times d \times e = f$

TOTAL MACHINE RUN -
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Table B-2 9" Cutter, 8 Teeth, Retrofit 100 HP, 3600 RPM, 200°F

MACHINE RUN CALCULATIONS

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NOTE: $a + b = c \times d \times e = f$

Table B-3 9" Cutter, 8 Teeth, Retrofit 100 HP, 12,000 RPM, 200 FPM

MACHINE RUN CALCULATIONS

NOTE: $a + b = c \times d \times e = f$

TOTAL MACHINE RUN -
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Table B-4 14" Wheel Cutter (Roughing), 9" (Finishing), 100 HP & 150 HP.

NOTE: $a + b = c \times d \times e = f$

Table B-5 9" Diameter Cutter, 8 Teeth, 150 HP, 3600 RPM

MACHINE RUN CALCULATIONS

NOTE: $a + b = c \times d \times e = f$

B-6

TOTAL MACHINE RUN -
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Table B-6 9" Diameter Cutter, 8 Teeth, 75HP, 2000 RPM

MACHINE RUN CALCULATIONS

NOTE: $a + b = c \times d \times e = f$

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B-7

TOTAL MACHINE RUN -
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Table B-7 9" Diameter Cutter, 8 Teeth, 100 HP, 12,000 RPM

MACHINE RUN CALCULATIONS

NOTE: $a + b = c \times d \times e = f$

Table B-8 9" Diameter Cutter, 8 Teeth, 150 HP, 24,000 RPM

MACHINE RUN CALCULATIONS

NOTE: $a + b = c \times d \times e = f$

B-9

TOTAL MACHINE RUN -
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APPENDIX C

FLOOR-TO-FLOOR MACHINING TIME AND MONTHLY PANEL MACHINING CAPACITY

- C-1 One Spindle Machine - One Panel Length Table
- C-2 Two Spindle Machine (Machining One Panel) -
One Panel Length Table
- C-3 Four Spindle Machine (Machining Two Panels) -
One Panel Length Table
- C-4 One Spindle Machine - Two Panel Length Table
- C-5 Two Spindle Machine - Two Panel Length Table
- C-6 Four Spindle Machine - Two Panel Length Table

Table C-1. Total Floor-to-Floor Machining Time and Monthly Panel Machining Capacity
One Spindle Machine

MACHINE TOOL CONFIGURATIONS									
RETROFIT		NEW		HIGH SPEED MACHINING					
CONV.		HSM		CONVENTIONAL		Vertical Spindle 150 hp 3600 rpm		Vertical Spindle 150 hp 24000 rpm	
PRESENT 1 Spindle	Existing	Existing	Existing	Horiz. for Rough Vert. for Finish	Vertical Spindle 150 hp 3600 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm
Cutters*	5 $\frac{1}{4}$ " Rough 6 Finish	9"	9"	Rough Finish & Finish	14" Rough **9" Finish	9" Rough Finish & Finish	9" Rough Finish & Finish	9" Rough Finish & Finish	2" Rough 9" Finish
PARAMETERS									
Machining Time (hours)	52.468	10.493	5.020	11.367	9.758	5.906	4.755	2.710	2.860
Break, Fatigue and Personal Time (hrs) (20% of Machining Time)	10.494	2.099	1.004	2.273	1.952	1.181	.951	.542	.572
Shop Machining Time (hours)	62.962	12.592	6.024	13.640	11.710	7.087	5.706	3.252	3.432
Panel Loading and Unloading Time (hours)	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Total Floor-To- Floor Time (hours)	<u>65.962</u>	<u>15.592</u>	<u>9.024</u>	<u>16.640</u>	<u>14.710</u>	<u>10.087</u>	<u>8.706</u>	<u>6.252</u>	<u>6.432</u>
Monthly Panel Capacity/2 Shifts (no. panels)	4.9	19.5	36.1	19.6	22.1	32.3	37.4	52.1	50.6

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Table C-2. Total Floor-to-Floor Machining Time and Monthly Panel Machining Capacity
 Two Spindle Machine (Machining One Panel)

One Panel Length Table

PARAMETERS	RETROFIT		CONVENTIONAL		HIGH SPEED MACHINING		MACHINE TOOL CONFIGURATIONS
	PRESENT	CONV.	HSM	* Horiz. for Rough Vert. for Finish	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	
	Existing 20 hp 3600 rpm	Existing 100 hp 3600 rpm	Existing 100 hp 12000 rpm	100&150 hp 3600 rpm	150 hp 3600 rpm	150 hp 24000 rpm	
Cutters*	5 $\frac{1}{4}$ " Rough & Finish	9" Rough & Finish	9" Rough & Finish	14" Rough 9" Finish	9" Rough 9" Finish	9" Rough 9" Finish	2" Rough 9" Finish
Machining Time (hrs) (inc. cutter positioning)	52.468 ref.	5.247	2.510	5.684	4.879	2.953	2.378
Break, Fatigue and Personal Time(hrs) 20% of Machining Time	10.494 ref.	1.049	.502	1.137	.976	.591	.476
Shop Machining Time (hours)	62.962 ref.	6.296	3.012	6.821	5.855	3.544	2.854
Panel Loading and Unloading Time (hours)	3.0 ref.	3.0	3.0	3.0	3.0	3.0	3.0
Total Floor-to-Floor Time (Hours)	65.962 ref.	9.296	6.012	9.821	8.855;	6.544	5.854
Monthly Panel Capacity/2 Shifts (No. Panels)	4.9 ref.	35.0	54.1	33.1	36.8	49.7	55.6

Table C-3. Total Floor-to-Floor Machining Time and Monthly Panel Machining Capacity
Four Spindle Machine (Machining Two Panels)

One Panel Length Table

PRESENT 1 Spindle	RETROFIT		MACHINE TOOL CONFIGURATIONS				HIGH SPEED MACHINING	
	CONV.	HSN	CONVENTIONAL		NEW			
	Existing	Existing	Horiz. for Rough Vert. for Finish	Vertical Spindle 150 hp 3600 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm		
Existing 20 hp 3600 rpm	100 hp 3600 rpm	100 hp 12000 rpm	100&150 hp 3600 rpm	Vertical Spindle 150 hp 3600 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm	
Cutters→ 5½" Rough & Finish	9" Rough & Finish	9" Rough & Finish	14" Rough 9" Finish	9" Rough 6" Finish	9" Rough 6" Finish	9" Rough & Finish	2" Rough 9" Fin. & h	
Machining Time (hrs)	52.468	-	-	2.897	2.478	1.651	.678	
Break, Fatigue and Personal Time (hrs) (20% of Machining Time)	10.494	-	-	.579	.496	.295	.136	
Shop Machining Time (hours)	62.962	-	-	3.476	2.974	1.946	.814	
Panel Loading and Unloading Time (hrs)	3.0	-	-	2.250	2.250	2.250	2.250	
Total Floor-to-Floor Time (hours)	65.962	-	-	5.726	5.224	4.196	3.743	
Monthly Panel Capacity	4.9	-	-	56.8	62.3	77.6	87.0	
2 Shifts (No. Panels)							104.7	

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Table C-4. Total Floor-to-Floor Machining Time and Monthly Panel Machining Capacity
 (One Spindle Machine)

Two Panel Length Table

PRESENT	RETROFIT		CONVENTIONAL.		NEW		HIGH SPEED MACHINING	
	CONV.	HSM	Horiz. for Rough Vert. for Finish	Vertical Spindle 100 & 150 hp 3600 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm
Existing	Existing	Existing	Horiz. for Rough Vert. for Finish	Vertical Spindle 100 & 150 hp 3600 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm
20 hp 3600 rpm	100 hp 3600 rpm	100 hp 12000 rpm	100 & 150 hp 3600 rpm	150 hp 3600 rpm	75 hp 9000 rpm	100 hp 12000 rpm	150 hp 24000 rpm	150 hp 24000 rpm
Cutters*	5 ^{1/2} " Rough & Finish	9" Rough & Finish	14" Rough 9" Finish	14" Rough 9" Finish	9" Rough 9" Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish
Machining Time (Hrs) (Incl. Cutter Positioning)	52.468	-	-	11.367	9.758	5.906	4.755	2.710
Break, Fatigue and Personal Time (Hrs) (20% of Machining Time)	10.494	-	-	2.273	1.952	1.181	.951	.542
Shop Machining Time (Hours)	<u>62.962</u>	-	-	<u>13.640</u>	<u>11.710</u>	<u>7.087</u>	<u>5.706</u>	<u>3.252</u>
Additional Panel Loading and Unloading Time (Hours)	-	-	0	0	0	0	0	0
Total Floor-to-Floor Time (Hours)	<u>65.962</u>	-	-	<u>13.640</u>	<u>11.710</u>	<u>7.087</u>	<u>5.706</u>	<u>3.252</u>
Monthly Panel Capacity/2 Shifts (# panels)	4.9	-	-	23.9	27.8	45.9	57.0	100.1
								94.8

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Table C-5. Total Floor-to-Floor Machining Time and Monthly Panel Machining Capacity
Two Spindle Machine

		Two Panel Table Length				
		MACHINE TOOL CONFIGURATIONS				
		RETROFIT		NEW		
PRESENT	CONV.	HSN!	CONVENTIONAL		HIGH SPEED MACHINING (HSM)	
Existing	Existing	Horiz. for Rough Vert. for Finish	Vertical Spindle 100 & 150 hp 3600 rpm	Vertical Spindle 75 hp 3600 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm
20 hp 3600 rpm	100 hp 3600 rpm	100 hp 12000 rpm	150 hp 3600 rpm	150 hp 3600 rpm	100 hp 12000 rpm	150 hp 24000 rpm
CUTTERS	5½" Rough & Finish	9" Rough & Finish	14" Rough 9" Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish
Machining Time (hrs) (incl. cutter Positioning)	52.468	-	5.684	4.879	2.953	2.378
Break, Fatigue and Personal Time (Hrs) (20% of Machining Time)	10.494	-	-	1.137	.976	.591
Shop Machining Time (hours)	<u>62.962</u>	-	<u>6.821</u>	<u>5.855</u>	<u>3.544</u>	<u>2.854</u>
Additional Panel Loading and Unloading Time (hours)	-	-	0	0	0	.146
Total Floor-to-floor Time (hours)	<u>65.962</u>	-	<u>6.821</u>	<u>5.855</u>	<u>3.544</u>	<u>2.854</u>
Monthly Panel Capacity/2 Shifts (# Panels)	4.9	-	47.7	55.6	91.8	(114.1)

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(XXX) Values not limited by load/unload times

Table C-6. Total Floor-to-Floor Machining Time and Monthly Panel Machining Capacity
Four Spindle Machine

		Two Panel Length Table					
		Machine Tool Configurations					
		Conventional			High Speed Machining		
Present	Retrofit	Conv.	HSM				
		Existing	Existing	Horiz. for Rough Vert. for Finish 100 & 150 hp 3600 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm
		20 hp 3600 rpm	100 hp 3600 rpm	100 & 150 hp 3600 rpm	150 hp 3600 rpm	150 hp 24000 rpm	150 hp 24000 rpm
Parameters	Cutters+	5½" Rough & Finish	9" Rough & Finish	14" Rough 9" Finish	9" Rough 6 Finish	9" Rough & Finish	2" Rough 9" Finish
Machining Time (Hrs) (Incl. Cutter Positioning)	52.468	-	-	2.894***	2.478**	1.651	1.255
Break, Fatigue and Personal Time (Hrs) (20% of Machining Time)	10.494	-	-	.579	.496	.295	.238
Shop Machining Time (hours)	62.962	-	-	3.476	2.974	1.946	1.493
Additional Panel Loading and Unloading Time (hours)	-	-	-	0	0	.304	.757
Total Floor-to-Floor Time (hours)	65.962	-	-	3.476	2.974	2.250	2.250
Monthly Panel Capacity/2 Shifts (# Panels)	4.9	-	-	93.6	109.4	(1.493) (.814)	(.814) (.858)
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(XXX) Values not limited by load/unload time							
*** Values limited by gantry feed							

APPENDIX D

LABOR COSTS

- D-1 Cost per Panel and Per 5,376 Panels -
 One Panel Length Table**
- D-2 Labor Cost Per Panel and Per 5,376 Panels -
 Two Panel Length Tables**

Table D-1. Cost (\$): Per Panel and Per 5,376 Panels

One Panel Length Table

MACHINE TOOL CONFIGURATIONS							
PRESENT	RETROFIT		CONVENTIONAL		HIGH SPEED MACHINING		
	CONV.	HSM	Horiz. for Rough Vert. for Finish 100&150 hp 3600 rpm	Vertical Spindle 150 hp 3600 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm
Existing	Existing	Existing	100 hp 3600 rpm	100 hp 12000 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm
20 hp 3600 rpm	100 hp 3600 rpm	100 hp 12000 rpm	100&150 hp 3600 rpm	150 hp 3600 rpm	150 hp 9000 rpm	100 hp 12000 rpm	150 hp 24000 rpm
Cutters+ 5½" Rough & Finish	9" Rough & Finish	9" Rough & Finish	14" Rough 9" Finish	9" Rough 9" Finish	9" Rough & Finish	9" Rough & Finish	2" Rough 9" Finish
PARAMETERS							
One Spindle							
Hours/Panel	65.962	15.592	9.024	16.640	14.710	10.087	8.706
\$/Panel	3,958	936	541	998	883	605	522
\$/5,376 Panels	21,278K	5,031K	2,908K	5,365K	4,474K	3,252K	2,806K
Two Spindle							
Hours/Panel	-	9.296	6.012	9.821	8.855	6.544	5.854
\$/Panel	-	558	361	589	531	393	351
\$/5,376 Panels	-	3,000K	1,941K	3,166K	2,855K	2,113K	1,887K
Four Spindle							
Hours/Panel	-	-	-	5.726	5.224	4.196	2.743
\$/Panel	-	-	-	344	252	225	184
\$/5376 Panels	-	-	-	1,849K	1,683K	1,355K	1,209K

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Table D-2. Labor Cost (\$): Per Panel and 5,376 Panels

Two Panel Length Table

(XXX) Values not limited by load/unload times

MACHINE TOOL CONFIGURATIONS

MACHINE TOOL CONFIGURATIONS									
	RETROFIT			NEW			HIGH SPEED MACHINING		
PRESENT	CONV.	HSN	CONVENTIONAL	Vertical Spindle	Vertical Spindle	Vertical Spindle	Vertical Spindle	Vertical Spindle	Vertical Spindle
(XXX) Values not limited by load/unload times			Horiz. for Rough Vert. for Finish 100hp 150hp 3600 rpm	Vertical Spindle 150 hp 3600 rpm	Vertical Spindle 100 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm
Existing	Existing	Existing	Vert. for Rough Finish 100 hp 3600 rpm	Vertical Spindle 150 hp 3600 rpm	Vertical Spindle 100 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm
20 hp 3600 rpm	100 hp 3600 rpm	100 hp 12000 rpm	100hp 150hp 3600 rpm	150 hp 3600 rpm	100 hp 9000 rpm	100 hp 12000 rpm	150 hp 24000 rpm	150 hp 24000 rpm	150 hp 24000 rpm
Cutters+ 5½" Rough & Finish	9" Rough & Finish	9" Rough & Finish	14" Rough 9" Finish	9" Rough 9" Finish	9" Rough 9" Finish	9" Rough 9" Finish	9" Rough 9" Finish	9" Rough 9" Finish	9" Rough 9" Finish
PARAMETERS									
<u>One Spindle</u>									
Hours/Panel	65.962	-	-	13.640	11.710	7.087	5.706	3.252	3.432
\$/Panel	3,958	-	-	818	703	425	342	195	206
\$/5376 Panels	21,278K	-	-	4,398K	3,779K	2,285K	1,839K	1,048K	1,107K
<u>Two Spindle</u>									
Hours/Panel	-	-	-	6,821	5,855	3,544	3,000	3,000	3,000
\$/Panel	-	-	-	409	351	213	180	180	180
\$/5,376 Panels	-	-	-	2,199K	1,887K	1,145K	(171)	(98)	(103)
<u>Four Spindle</u>									
Hours/Panel	-	-	-	3,476	2,974	(1.946)	(1.493)	(.814)	(.858)
\$/Panel	-	-	-	209	178	135	135	135	135
\$/5376 Panels	-	-	-	1.124K	957K	726K	726K	(484K)	(263K)

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APPENDIX E

MACHINE INVESTMENT COST

- E-1 One Spindle (One Panel Width) -
 One Panel Length Table**
- E-2 Two Spindle (One Panel Width) -
 One Panel Length Table**
- E-3 Four Spindle (Two Panel Width) -
 One Panel Length Table**
- E-4 One Spindle (One Panel Width) -
 Two Panel Length Table**
- E-5 Two Spindle (One Panel Width) -
 Two Panel Length Table**
- E-6 Four Spindle (Two Panel Width) -
 Two Panel Length Table**

Table E-1. Machine Investment Cost (\$) per Panel and per 5,376 Panels
One Spindle (One Panel Width)

One Panel Length Table

PRESENT	RETROFIT		MACHINE TOOL CONFIGURATIONS					
	CONV.		CONVENTIONAL		NEW		HIGH SPEED MACHINING	
	CUTTERS	5½"	HORIZ.	VERT. FOR ROUGH VERT. FOR FINISH	VERTICAL SPINDLE 150 HP 3600 RPM	VERTICAL SPINDLE 100 HP 12000 RPM	VERTICAL SPINDLE 150 HP 9000 RPM	VERTICAL SPINDLE 150 HP 24000 RPM
Existing	Existing	Existing	Horiz. for Rough Vert. for Finish	Vertical Spindle 150 hp 3600 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm
20 hp 3600 rpm	100 hp 3600 rpm	100 hp 12000 rpm	100&150 hp 3600 rpm	14" Rough 9" Finish	9" Rough 9" Finish & Finish	9" Rough & Finish	9" Rough & Finish	2" Rough 9" Finish
PARAMETERS	Cutters+ 5½" Rough & Finish	9" Rough & Finish	0	0	1,900K	1,750K	1,400K	1,400K
Cost of Machine (FOB Huntsville)	-	50K	235K	-	-	-	-	1,400K
Cost of Additions	-	-	-	225K	225K	225K	-	-
Vacuum Chuck (if separate)	-	1K	5K	72.5K	72.5K	72.5K	72.5K	72.5K
Installation (Incl. Foundation)	-	-	2K	12K	12K	12K	12K	12K
Debug and Test	-	51K	242K	2,209.5K	2,059.5K	1,709.5K	1,809.5K	1,484.5K
Total Additional Machine Cost	0	9	45	411	383	318	337	276
Total Additional Machine Cost/Panel (Based on 5,376 Panels)								276

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Table E-2. Machine Investment Cost (\$) per Panel and per 5,376 Panels
Two Spindle (One Panel Width)

One Panel Length Table

PARAMETERS	RETROFIT			CONVENTIONAL			HIGH SPEED MACHINING		
	CONV.	HSM	Existing	Horiz. for Rough	Vert. for Finish	Vertical Spindle 75 hp	Vertical Spindle 100 hp	Vertical Spindle 12000 rpm	Vertical Spindle 150 hp
PRESENT 1 Spindle									
Existing 20 hp 3600 rpm	100 hp 3600 rpm	100 hp 12000 rpm	100&150 hp 3600 rpm	150 hp 3600 rpm	150 hp 9000 rpm	100 hp 12000 rpm	100 hp 24000 rpm	150 hp 24000 rpm	150 hp 24000 rpm
Cutters+ 5 1/4" Rough & Finish	9" Rough & Finish	9" Rough & Finish	14" Rough 9" Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish
Cost of Machine	0	0	2,200K	1,900K	1,550K	1,850K	1,650K	1,650K	1,650K
Cost of Additions	-	100K	400K	-	-	-	-	-	-
Vacuum Chuck (If Separate)	-	-	-	225K	225K	225K	225K	225K	225K
Installation (Incl. Foundation)	-	1.5K	7.5K	73K	73K	73K	73K	73K	73K
Debug and Test	-	-	3K	13K	13K	13K	13K	13K	13K
Total Additional Machine Cost	-	101.5K	410.5K	2,511K	2,211K	1,861K	2,161K	1,736K	1,736K
Total Additional Machine Cost/Panel (Based on 5,376 Panels)	0	19	76	.467	411	346	402	323	323

Table E-3. Machine Investment Cost (\$) per Panel and per 5,376 Panels
Four Spindle (Two Panel Width)

One Panel Length Table

		MACHINE TOOL CONFIGURATIONS						
		RETROFIT			NEW			
PRESENT Spindle	CONV. HSN	CONVENTIONAL			HIGH SPEED MACHINING			
		Horiz. for Rough Vert. for Finish	Vertical Spindle 150 hp 3600 rpm	Vertical Spindle 100 hp 9000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 100 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm	
Existing	Existing	Existing	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 75 hp 12000 rpm	Vertical Spindle 100 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm	
20 hp 3600 rpm	100 hp 3600 rpm	100 hp 3600 rpm	100 hp 3600 rpm	100 hp 9000 rpm	100 hp 24000 rpm	100 hp 24000 rpm	100 hp 24000 rpm	
20 hp 3600 rpm	100 hp 3600 rpm	100 hp 3600 rpm	100 hp 3600 rpm	100 hp 9000 rpm	100 hp 24000 rpm	100 hp 24000 rpm	100 hp 24000 rpm	
5½" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	
PARAMETERS								
Cost of Machine (FOB Huntsville)	-	-	3,100K	2,400K	2,400K	2,500K	2,500K	2,500K
Cost of Additions	-	-	-	-	-	-	-	-
Vacuum Chuck (If Separate)	-	-	400K	400K	400K	400K	400K	400K
Installation (Incl. Foundation)	-	-	82.5K	82.5K	82.5K	82.5K	82.5K	82.5K
Degub and Test	-	-	16.5K	16.5K	16.5K	16.5K	16.5K	16.5K
Total Machine Cost	-	-	3,599K	2,899K	2,899K	2,999K	2,999K	2,999K
Total Machine Cost/ Panel (based on 5,376 panels)	-	-	669	539	539	483	483	483

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Table E-4. Machine Investment Cost (\$) per Panel and per 5,376 Panels
One Spindle (One Panel Width)

		Two Panel Length Table					
		MACHINE TOOL CONFIGURATIONS			HIGH SPEED MACHINING		
		RETROFIT		CONVENTIONAL.		NEW	
PRESENT	CONV.	HSM!					
Existing	Existing	Existing	Horiz. for Rough Finish	Vertical Spindle 100 hp 3600 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm
20 hp 3600 rpm	100 hp 3600 rpm	100 hp 12000 rpm	100 hp 3600 rpm	150 hp 3600 rpm	150 hp 9000 rpm	150 hp 12000 rpm	150 hp 24000 rpm
Cutters+ Slit" Rough & Finish	9" Rough & Finish	9" Rough & Finish	14" Rough 9" Finish	9" Rough 9" Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish
PARAMETERS							
Cost of Machine (FOB Huntsville)	-	-	2,150K	2,000K	1,550K	1,650K	1,550K
Cost of Additions	-	-	-	-	-	-	-
Vacuum Chuck (if separate)	-	-	400K	400K	400K	400K	-
Installation (Incl. Foundation)	-	-	82.5K	82.5K	82.5K	82.5K	82.5K
Debug and Test	-	-	12K	12K	12K	12K	12K
Total Machine Cost	-	-	2,644.5K	2,494.5K	2,044.5K	2,144.5K	1,644.5K
Total Machine Cost/ Panel (Based on 5,376 Panels)	-	-	492	464	380	399	306
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Table E-5. Machine Investment Cost (\$) per Panel and per 5,376 Panels
Two Spindle (One Panel Width)

Two Panel Length Table

PRESENT	RETROFIT		MACHINE TOOL CONFIGURATIONS					
	CONV.		NEW		HIGH SPEED MACHINING			
	HSM		CONVENTIONAL		Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm
Existing	Existing	Existing	Horiz. for Rough	Vertical Spindle	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm
20 hp 3600 rpm	100 hp 3600 rpm	100 hp 12000 rpm	Vert. for Finish	100@150 hp 3600 rpm	150 hp 3600 rpm	100 hp 12000 rpm	150 hp 24000 rpm	150 hp 24000 rpm
Cutters+ 5 ¹ / ₂ " Rough & Finish	9" Rough & Finish	9" Rough & Finish	14" Rough 9" Finish	9" Rough 9" Finish	9" Rough 9" Finish	9" Rough 9" Finish	9" Rough 9" Finish	9" Rough 9" Finish
PARAMETERS								
E-6								
Cost of Machine (FOB Huntsville)	-	-	2,450K	2,150K	1,700K	2,000K	1,800K	1,800K
Cost of Additions	-	-	-	-	-	-	-	-
Vacuum Chuck (If Separate)	-	-	-	400K	400K	400K	400K	400K
Installation (Incl. Foundation)	-	-	-	85K	85K	85K	85K	85K
Debug and Test	-	-	-	13K	13K	13K	13K	13K
Total Machine Cost	-	-	-	2,948K	2,648K	2,198K	2,498K	1,898K
Total Machine Cost/ Panel (based on 5,376 panels)	-	-	-	548	493	409	465	353
								353

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Table E-6. Machine Investment Cost (\$) per Panel and per 5,376 Panels
Four Spindle (Two Panel Width)

Two Panel Length Table

		MACHINE TOOL CONFIGURATIONS					
		NEW			HIGH SPEED MACHINING		
		CONVENTIONAL		Vertical Spindle		Vertical Spindle	
PRESENT		Horiz. for Rough	Vertical Spindle	Vertical Spindle	Vertical Spindle	Vertical Spindle	Vertical Spindle
RETROFIT		Vert. for Finish	150 hp	100 hp	100 hp	150 hp	150 hp
CONV.		Finish	3600 rpm	1000 rpm	9000 rpm	12000 rpm	24000 rpm
HSN		1000 rpm	3600 rpm	1000 rpm	9000 rpm	12000 rpm	24000 rpm
Existing	Existing	Existing	Vertical Spindle	Vertical Spindle	Vertical Spindle	Vertical Spindle	Vertical Spindle
20 hp	100 hp	100 hp	150 hp	100 hp	100 hp	150 hp	150 hp
3600 rpm	3600 rpm	12000 rpm	3600 rpm	3600 rpm	9000 rpm	12000 rpm	24000 rpm
Cutters→	5½" Rough & Finish	9" Rough & Finish	14" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish
PARAMETERS							
Cost of Machine (FOB Huntsville)	-	-	-	3,400K	2,700K	2,700K	2,800K
Cost of Additions	-	-	-	-	-	-	-
Vacuum Chuck (if separate)	-	-	-	700K	700K	700K	-
Installation (Inc. Foundation)	-	-	-	90K	90K	90K	90K
Debug and Test	-	-	-	16.5K	16.5K	16.5K	16.5K
Total Machine Cost	-	-	-	4,206.5K	3,506.5K	3,606.5K	2,906.5K
Total Machine Cost/Panel (Based on 5,376 Panels)	-	-	-	782	652	671	541

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APPENDIX F

MACHINE INVESTMENT PLUS LABOR COSTS

- F-1 One Panel Length Table - One Spindle
- F-2 One Panel Length Table - Two Spindles
- F-3 One Panel Length Table - Four Spindles
- F-4 Two Panel Length Table - One Spindle
- F-5 Two Panel Length Table - Two Spindles
- F-6 Two Panel Length Table - Four Spindles

Table F-1. Combined Machine Investment Plus Labor per Panel and per 5,376 Panels (\$)

One Panel Length Table - One Spindle

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MACHINE TOOL CONFIGURATIONS									
	RETROFIT			NEW			HIGH SPEED MACHINING		
PRESENT	CONV.	HSM	CONVENTIONAL	Horiz. for Rough	Vert. for Rough	Vertical Spindle 75 hp	Vertical Spindle 100 hp	Vertical Spindle 150 hp	Vertical Spindle 24000 rpm
Existing	Existing	Existing	Vert. Spindle 150 hp 100 hp 3600 rpm	Vert. Spindle 150 hp 100 hp 3600 rpm	Vert. Spindle 150 hp 100 hp 3600 rpm	Vert. Spindle 100 hp 9000 rpm	Vert. Spindle 12000 rpm	Vert. Spindle 150 hp	Vert. Spindle 24000 rpm
20 hp 3600 rpm	100 hp 3600 rpm	100 hp 12000 rpm	100 hp 3600 rpm	100 hp 3600 rpm	100 hp 3600 rpm	100 hp 9000 rpm	100 hp 12000 rpm	100 hp 150 hp	100 hp 24000 rpm
Cutters [†]	5 $\frac{1}{4}$ " Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish
PARAMETERS									
One Spindle									
Machine Cost/Panel	0	9	45	411	383	318	337	276	276
Labor Cost/Panel	3,958	936	541	998	883	605	522	375	386
Total Cost/Panel	3,958	945	586	1,409	1,266	923	859	651	662
Machine Cost/5,376 Panels	0	51K	242K	2,210K	2,060K	1,710K	1,810K	1,485K	1,485K
Labor Cost/5,376 Panels	21,278K	5,031K	2,908K	5, 65K	4,747K	3,252K	2,806K	2,016K	2,075K
Total Cost/5,376 Panels	21,278K	5,082K	3,150K	7,575K	6,807K	4,962K	4,616K	3,501K	3,560K

Table F-2. Combined Machine Investment Plus Labor Cost (\$) Per Panel and Per 5,376 Panels

One Panel Length Table - Two Spindles

		MACHINE TOOL CONFIGURATIONS							
		RETROFIT			NEW			HIGH SPEED MACHINING	
PRESENT	CONV.	CONVENTIONAL		Vertical Spindle		Vertical Spindle		Vertical Spindle	
	HSM	Horiz. for Rough	Vert. for Finish	150 hp 3600 rpm	75 hp 9000 rpm	100 hp 12000 rpm	150 hp 24000 rpm	150 hp 24000 rpm	150 hp 24000 rpm
Existing	Existing	100 hp 3600 rpm	100 hp 12000 rpm	100&150 hp 3600 rpm	75 hp 9000 rpm	100 hp 12000 rpm	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish
20 hp 3600 rpm	20 hp 3600 rpm	100 hp 3600 rpm	100 hp 12000 rpm	100&150 hp 3600 rpm	75 hp 9000 rpm	100 hp 12000 rpm	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish
CUTTERS†	5½" Rough & Finish	9" Rough & Finish	9" Rough & Finish	14" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish
	5½" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish
Two Spindle		19	76	467	411	346	402	323	323
		558	361	589	531	393	351	278	283
		577	437	1,056	942	739	753	879	806
Machine Cost/Panel									
Labor Cost/Panel									
Total Cost/Panel									
Machine Cost/5,376 Panels		102K	411K	2,511K	1,861K	2,161K	1,736K	1,736K	1,736K
Labor Cost/5,376 Panels		3,000K	1,941K	3,166K	2,855K	2,113K	1,887K	1,495K	1,521K
Total Cost/5,376 Panels		3,102K	2,352K	5,677K	5,066K	3,974K	4,048K	3,231K	3,257K

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Table F-3. Combined Machine Investment Plus Labor Cost (\$) Per Panel and Per 5,376 Panels

One Panel Length Table - Four Spindles									
MACHINE TOOL CONFIGURATIONS									
PRESENT	RETROFIT		CONVENTIONAL		NEW		HIGH SPEED MACHINING		
	CONV.	HSM	Horiz. for Rough Vert. for Finish	Vertical Spindle 150 hp 3600 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm
Existing	Existing	Existing	Vertical Spindle 100 & 150 hp 3600 rpm	Vertical Spindle 150 hp 3600 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm
20 hp 3600 rpm	100 hp 3600 rpm	100 hp 12000 rpm	100 & 150 hp 3600 rpm	150 hp 3600 rpm	75 hp 9000 rpm	100 hp 12000 rpm	150 hp 24000 rpm	150 hp 24000 rpm	150 hp 24000 rpm
Cutters ^a	5½" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish
Four Spindle									
Machine Cost/Panel	-	-	669	533	539	558	483	483	483
Labor Cost/Panel	-	-	344	212	252	225	184	184	186
Total Cost/Panel	-	-	1,013	852	791	783	667	667	669
Machine Cost/5,376 Panels	-	-	3,599K	2,899K	2,899K	2,999K	2,599K	2,599K	2,559K
Labor Cost/5,376 Panels	-	-	1,849K	1,683K	1,355K	1,209K	989K	989K	1,000K
Total Cost/5,376 Panels	-	-	5,448K	4,582K	4,254K	4,208K	3,588K	3,588K	3,599K

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Table F-4. Combined Machine Investment Plus Labor Cost (\$)
Per Panel and Per 5,376 Panels

Two Panel Length Table - One Spindle							
MACHINE TOOL CONFIGURATIONS							
RETROFIT		CONVENTIONAL		HIGH SPEED MACHINING			
PRESENT	CONV.	HSM					
Existing	Existing	Existing	Horiz. for Rough Vert. for Finish	Vertical Spindle 150 hp 9000 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm
20 hp 3600 rpm	100 hp 3600 rpm	100 hp 12000 rpm	100&150 hp 3600 rpm	14" Rough 9" Finish & Finish	9" Rough 9" Finish & Finish	9" Rough & Finish	2" Rough 9" Finish
CUTTERS	5½" Rough & Finish	9" Rough & Finish					
PARAMETERS							
<u>One Spindle</u>							
Machine Cost/Panel	-	-	492	464	380	399	306
Labor Cost/Panel	-	-	818	703	425	342	195
Total Cost/Panel	-	-	1,310	1,167	1,972	741	501
Machine Cost/5,376 Panels	-	-	2,645K	2,495K	2,045K	2,145K	1,645K
Labor Cost/5,376 Panels	-	-	4,398K	3,779K	2,285K	1,839K	1,048K
Total Cost/5,376 Panels	-	-	7,043K	6,274K	4,330K	3,984K	2,693K
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2,752K							

Table F-5. Combined Machine Investment Plus Labor Cost (\$)
Per Panel and Per 5,376 Panels

Two Panel Length Table - Two Spindles									
(XXX) Values not limited by load/unload times	MACHINE TOOL CONFIGURATIONS								
	RETROFIT			CONVENTIONAL			HIGH SPEED MACHINING		
	PRESENT	CONV.	HSM	Horiz. for Rough Vert. for Finish	Vertical Spindle 150 hp 3600 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm
Existing ^a	Existing	Existing	Existing	Vertical Spindle 150 hp 3600 rpm	Vertical Spindle 150 hp 3600 rpm	Vertical Spindle 75 hp 9000 rpm	Vertical Spindle 100 hp 12000 rpm	Vertical Spindle 150 hp 24000 rpm	Vertical Spindle 150 hp 24000 rpm
20 hp 3600 rpm	100 hp 3600 rpm	100 hp 12000 rpm	100 hp 12000 rpm	100 hp 3600 rpm	100 hp 3600 rpm	100 hp 9000 rpm	100 hp 12000 rpm	100 hp 24000 rpm	100 hp 24000 rpm
Cutters ^b	5 $\frac{1}{4}$ " Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish	9" Rough & Finish
Two Spindle	-	-	-	548	493	409	465	353	353
Machine Cost/Panel	-	-	-	409	351	213	180	180	180
Labor Cost/Panel	-	-	-				(171)	(98)	(103)
Total Cost/Panel	-	-	-	957	844	622	645	533	533
Machine Cost/5,376 Panels	-	-	-	2,948K	2,648K	2,198K	2,498K	1,898K	1,898K
Labor Cost/5,376 Panels	-	-	-	2,199K	1,887K	1,145K	968K	968K	968K
Total Cost/5,376 Panels	-	-	-	5,147K	4,535K	3,343K	3,466K	2,866K	2,866K

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Table F-6. Combined Machining Investment Plus Labor Cost (\$)
Per Panel and Per 5,376 Panels

		Two Panel Length Table - Four Spindles											
		Machine Tool Configurations											
		Conventional				High Speed Machining (HSM)							
		Retrofit				New							
Present	CONV.	HSM	Conventional				High Speed Machining (HSM)						
(XXX) Values not limited by load/unload times			Horiz. for Rough Vert. for Finish				Vertical Spindle 75 hp 9000 rpm						
Existing	Existing	Existing	Vertical Spindle 150 hp 3600 rpm				Vertical Spindle 100 hp 12000 rpm						
20 hp 3600 rpm	100 hp 3600 rpm	100 hp 12000 rpm	Vertical Spindle 150 hp 3600 rpm				Vertical Spindle 150 hp 24000 rpm						
Cutters+ 5 1/4" Rough & Finish	9" Rough & Finish	9" Rough & Finish	14" Rough 9" Finish				9" Rough 6" Finish						
Four Spindle			9" Rough 9" Finish				9" Rough 6" Finish						
Machine Cost/Panel	-	-	782				652						
Labor Cost/Panel	-	-	209				178						
Total Cost/Panel	-	-	991				830						
Machine Cost/5,376 Panels	-	-	4,207K				3,507K						
Labor Cost/5,376 Panels	-	-	1,124K				957K						
Total Cost/5,376 Panels	-	-	5,331K				4,464K						
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F-7													
Machine Cost/5,376 Panels	-	-	4,233K				3,333K						
Labor Cost/5,376 Panels	-	-	(4,136K)				(4,091K)						
Total Cost/5,376 Panels	-	-	(4,136K)				(3,170K)						
			(3,181K)				(3,181K)						
			3,633K				3,633K						

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TASK B
FINAL REPORT

HIGH-SPEED MACHINING OF
SPACE SHUTTLE EXTERNAL TANK
(ET) PANELS

15 SEPTEMBER 1982

Prepared for

National Aeronautics & Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Prepared by:

Joseph A. Miller
Missile Systems Division

Contract: NAS8-34508

FOREWORD

Lockheed Missiles & Space Company, Inc. is pleased to submit this Task B final report to the National Aeronautics & Space Administration, Marshall Space Flight Center in accordance with Contract Number NAS8-34508.

The program, summarized herein, covers Task B of the contract, plus changes specified by Change Orders No. 1 and No. 3. Change Order No. 1 essentially added the high-speed machining of an 8 foot long panel (Ref NASA letter of 18 December 1981 by James D. Hankins) and transferred the activity of Task A identified by the paragraph "Identify Potential High-Speed Milling Procedures" to Task B where it is entitled "High-Speed Milling Procedures and Times". Change Order No. 3 added video taping of the high-speed machining panel cutting process.

This submission is not intended to duplicate a Task A* report and documents only the results of the Task B activities.

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* See Task A objectives under Introduction

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Section 1

INTRODUCTION

The External Fuel Tank (ET) of the Space Shuttle (see Figures 1-1 and 1-2) is not recovered after launch, therefore, a new one must be provided each time. Currently, the external "skin" panels of the tank are produced by machining from solid wrought 2219-T87 aluminum plate stock approximately 1-3/4 in. thick.

The reduction of costs in producing External Fuel Tank panels is obviously, then, of particular significance. This study which is divided into Tasks A and B was initiated to investigate the feasibility of increasing production rates and decreasing costs of the panels through the application of high-speed machining techniques.

1-1 TASK A OBJECTIVES

Task A, which has not yet been performed, is designed to address anticipated cost savings from converting to high-speed machining techniques from the current conventional machining process in manufacturing Shuttle External Tank panels. The cost savings are to be projected from conventional machining data and high-speed machining data generated and projected during Task B activities.

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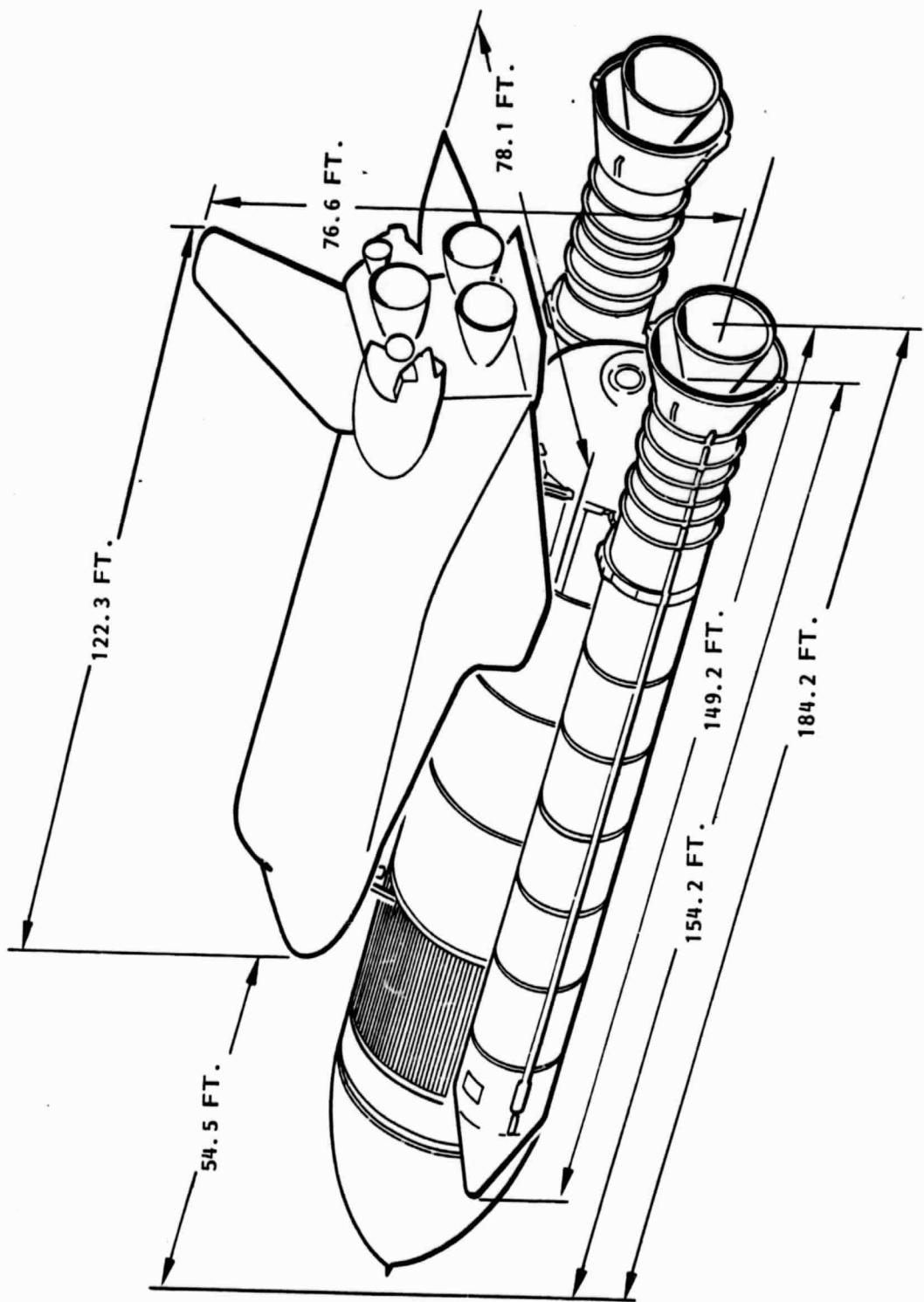


Figure 1-1 Space Shuttle Attached to External Fuel Tank

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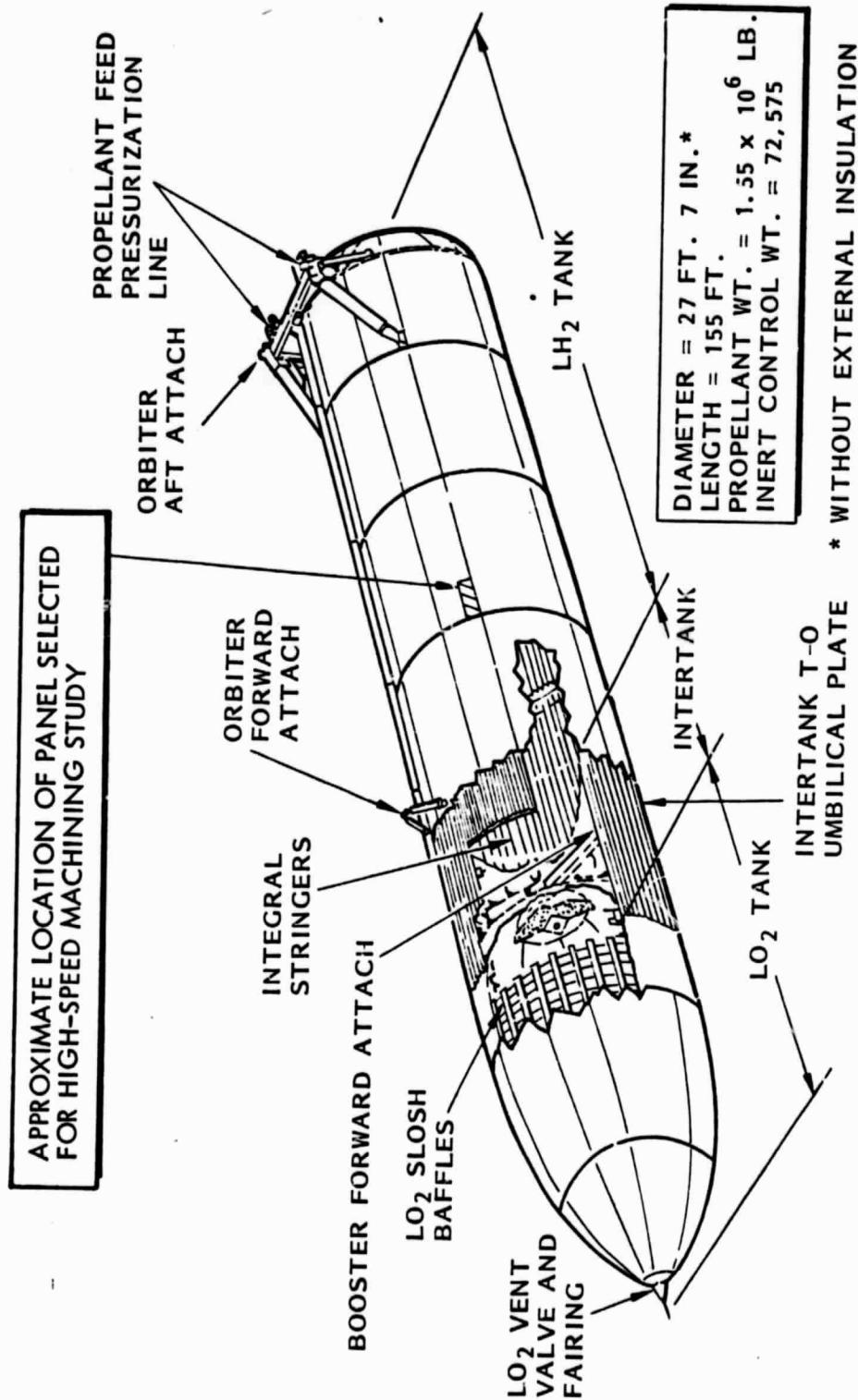


Figure 1-2 Detail of Space Shuttle External Fuel Tank

1-2 TASK B OBJECTIVES

The primary objective of Task B (the subject of this report) was to demonstrate the applicability and advantages of the high-speed machining process to the production of Shuttle External Tank panels by physically machining selected sample portions of an external tank panel. Figure 1-1 shows the relationship of the Shuttle to the External Tank to which it is attached for launching. The approximate location of the sample panel portion selected for this study is illustrated in Figure 1-2.

Section 2
TASK B TASKS

The elements of Task B as delineated in the original contract are as follows:

- 1) Select the panel sample configuration
- 2) Perform the milling demonstration
- 3) Produce a Task B final report

The scope of Task B was subsequently increased through Change Order No. 1 to include two additional tasks. The fourth task is the machining of an 8 foot long panel section, and the fifth, to incorporate the paragraph from Task A entitled "Identify Potential High-Speed Milling Procedures." This paragraph was relabelled "High-Speed Milling Procedures and Times".

A sixth task, the video taping of the high-speed machining process, was added by means of Change Order No. 3.

2-1 DELIVERABLE HARDWARE

The deliverable items under Task B of the contract are as follows:

- 1) 3 - 38 in. x 46-1/2 in. (approximately) tank panel sections
- 2) 1 - 38 in. x 94-1/2 in. (approximately) tank panel section
- 3) Several small T-rib cross-sections of sample panel
- 4) Video tape of high-speed machining panel cutting operation
 - a) Original footage (with written narration)
 - b) Rough edited version (with written narration)

Section 3
TASK B TECHNICAL APPROACH

A primary objective of the panel cutting of Task B was to demonstrate the advantage of high-speed machining for Shuttle tank panels within the limitations of equipment available at Lockheed and then to project to an ideal situation where equipment would be especially designed or adapted for this purpose.

3-1 EQUIPMENT LIMITATIONS

The only milling machines available at Lockheed, which were large enough to machine the panel samples selected, were the Sundstrand Omnimil NC machining centers. A model OM3 (Figure 3-1) was selected for the preliminary cutter and NC tape trials because of its availability and accessibility. However, a model OM4 (Figure 3-13) was required to accommodate the larger sizes during the final panel machining.

3-1.1 Table Feed

The maximum table feed capability of both the OM3 and OM4 Sunstrand models is 200 inches per minute (ipm) which is definitely a limiting factor when high-speed machining aluminum under these conditions. Higher cutting speeds (sfpm) could be attained by increasing the spindle speed; however, the volume of metal would not be significantly increased because the chip load would be simultaneously reduced unless the table feed could be increased accordingly.

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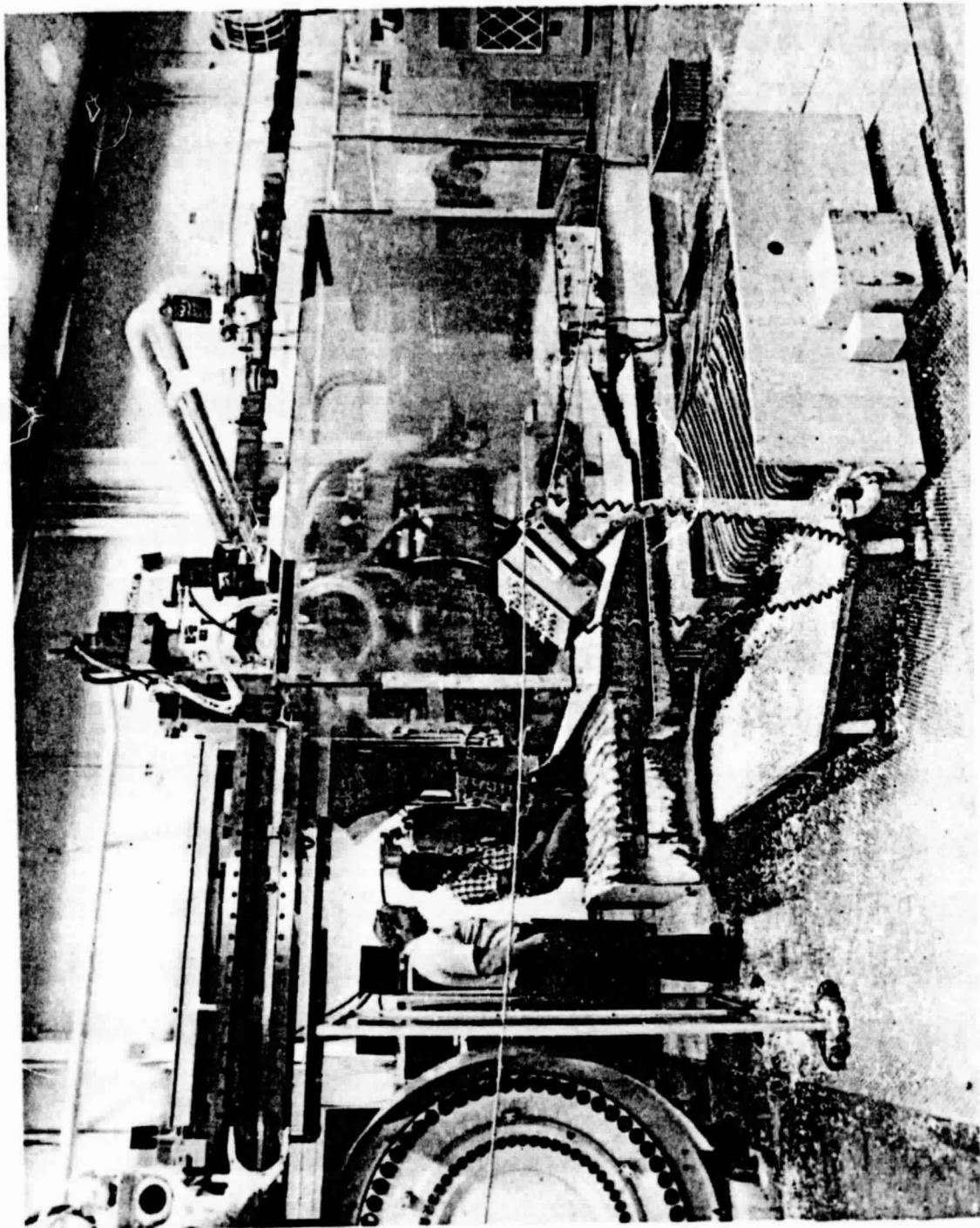


Figure 3-1 High Speed Machining Cutter Trials on Sundstrand OM3 NC Machining Center

3-1.2 Horsepower

Horsepower was also a limiting factor (16.6 hp maximum at 18,000 rpm and 5.5 hp at 8,000 rpm). If more horsepower had been available, more volume (cu in/min) of metal could have been removed by utilizing heavier depths of cut, larger diameter cutters, and higher feed rates.

3-1.3 Spindle Nose Configuration

The No. 30 Milling Machine Taper (MMT) of the Bryant 18,000 rpm spindle motor (Figure 3-2) was definitely a limiting factor in that the tool holder shank diameter of only 1-1/4 in. at the large end of the taper restricted the size of cutter which could be employed. This relatively small spindle nose also restricted the shank diameter of the cutting tool itself, thus automatically limiting the length of tool and depth of cut which could be utilized due to a lack of rigidity and/or stiffness.

3-1.4 Table Travel

The table travel of Lockheed's largest capacity machining center, the Sundstrand OM4, limited the size of panel which could be machined. When laying the panels down flat on the OM4 machine table (Figures 3-3 and 3-4), the maximum panel size attainable was 21 in. by 96 in. Consequently, the 38-in. finished panel width was achieved only by machining half of the panel width and then indexing to reach the second half.

3-1.5 Chip Removal Not Automated

The fact that the chip removal was not automated was not actually a substantial limiting factor for the sizes of panels involved in the project. However, for full-size Shuttle Tank panels, a conveyor system plus a system of

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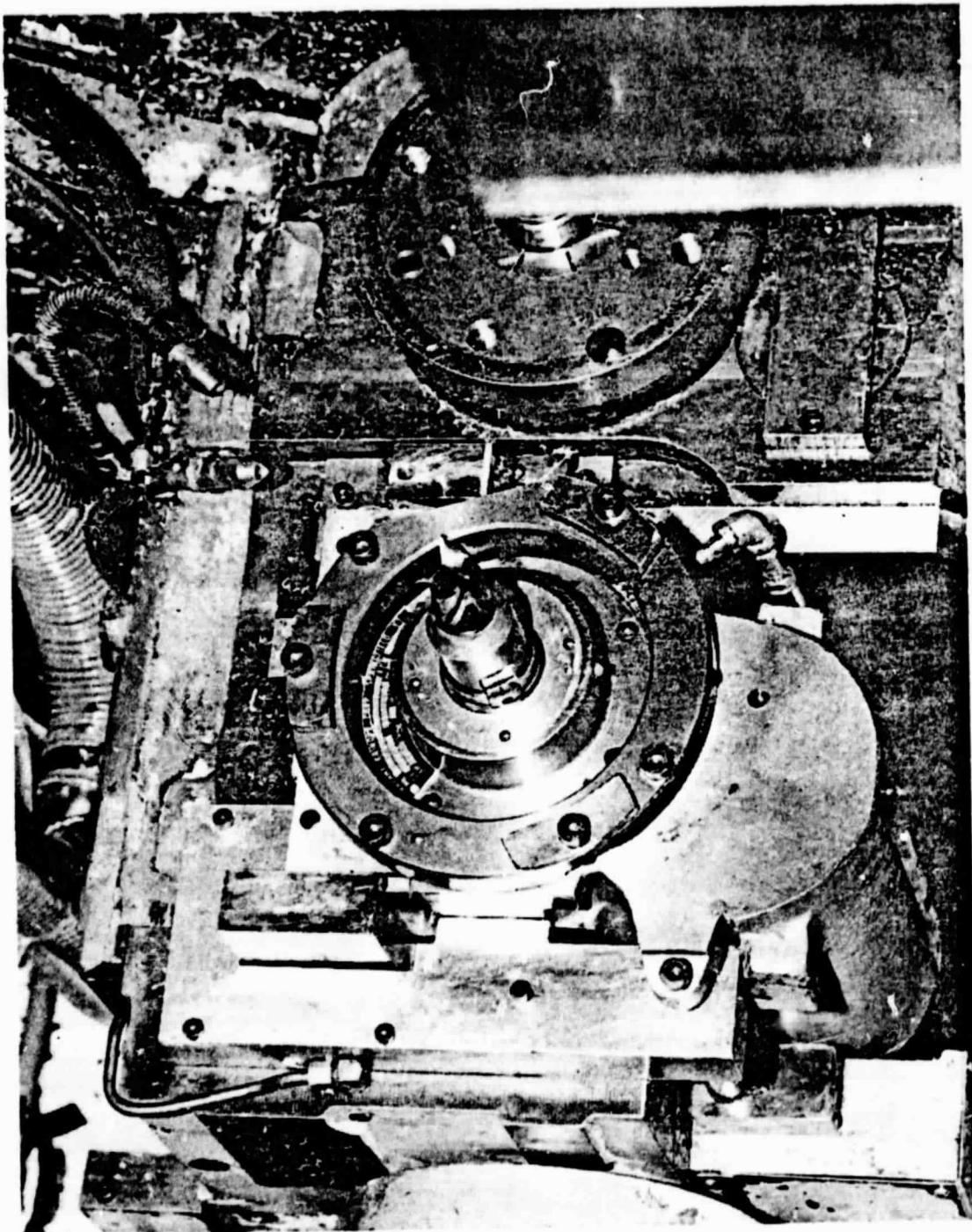


Figure 3-2 Close-up of 18,000 RPM Bryant Spindle Motor Installed in OMS

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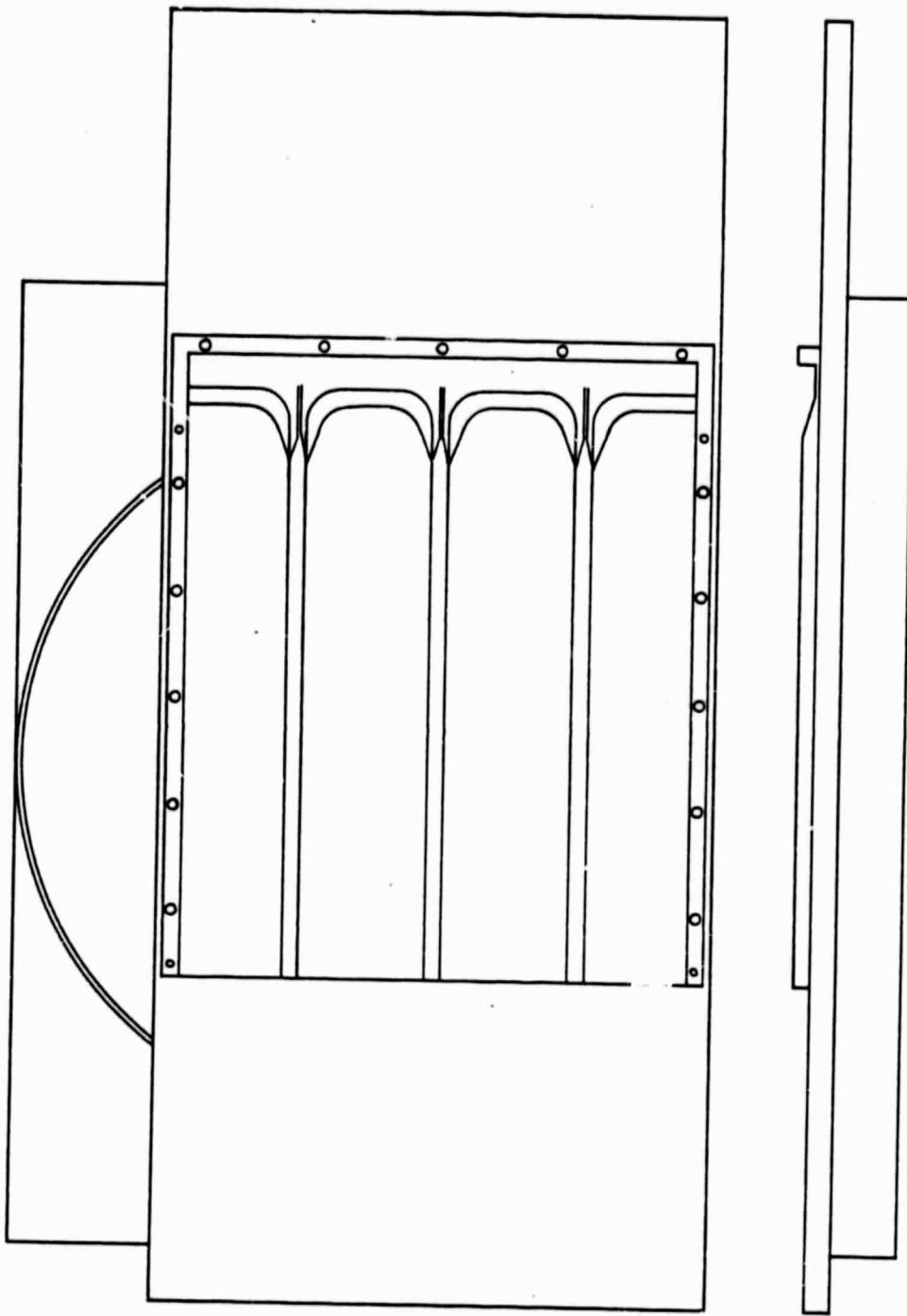


Figure 3-3 4 Ft Long Panel as Positioned on Base Plate and Machine Table

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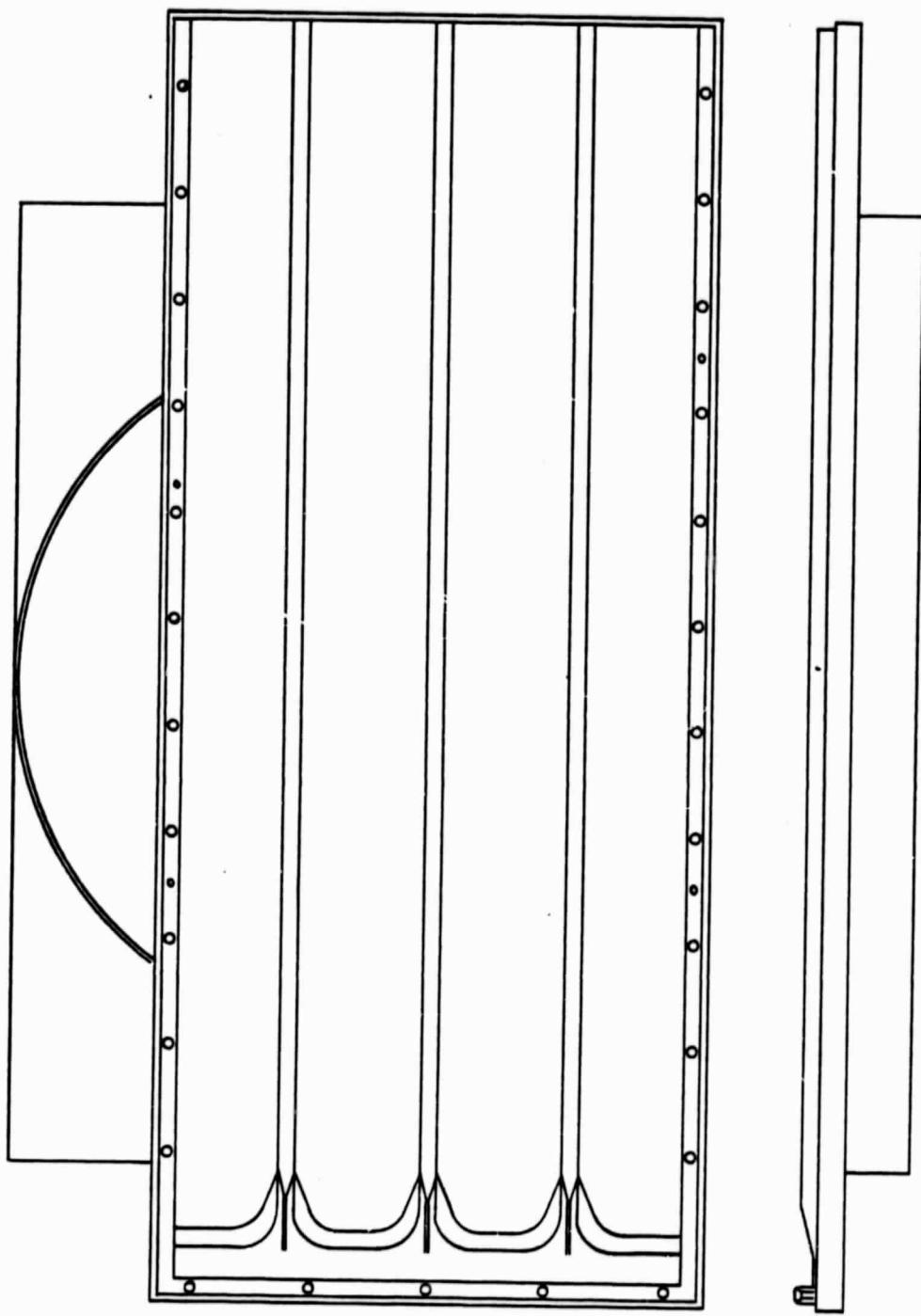


Figure 3-4 8 Ft Long Panel as Positioned on Base Plate and Machine Table

flood coolant or air blast nozzles to move the chips to the conveyor would be recommended. Perhaps an even more functional approach for chip removal would be the use of a sufficiently powerful vacuum system to vacuum away the chips.

3-2 PANEL SELECTION

The selection of a specific Shuttle External tank panel which was felt to represent the majority of the panels (see Figures 1-1 and 1-2) was accomplished primarily by personnel from the Marshall Space Flight Center and their prime contractor for the Shuttle Tank, Martin Marietta. As the panels are generally 11 ft wide by 20 ft long, a full panel was not feasible for this study, especially in light of Lockheed's machine tool limitations. Therefore, approximately 4 ft by 4 ft and 4 ft by 8 ft sections of an appropriate panel were chosen. This panel is identified by Martin Marietta drawing number 80914400984 with selected sections indicated on Sheet 2. The configurations of these panel sections are shown in Figures 3-3, 3-4, and 3-5 of this report and in subsequent photographs.

Following the panel selection, 2219-T87 aluminum material for the study was shipped from Martin Marietta to Lockheed. (See Paragraph 3-4.1.1 for details).

3-3 CUTTER SELECTION AND TRIALS

The diameters of the cutters to be used in high-speed machining the sample panels were limited by the horsepower and other parameters of the available equipment (See 3-1). The cutters selected had been successfully tested previously at Lockheed for the high-speed machining of aluminum, but of a different alloy. These chosen cutter designs had to be modified for proper corner radii to meet the panel configuration and for shank diameter to be utilized in the tool holder acceptable for the high-speed spindle motor selected for the project.

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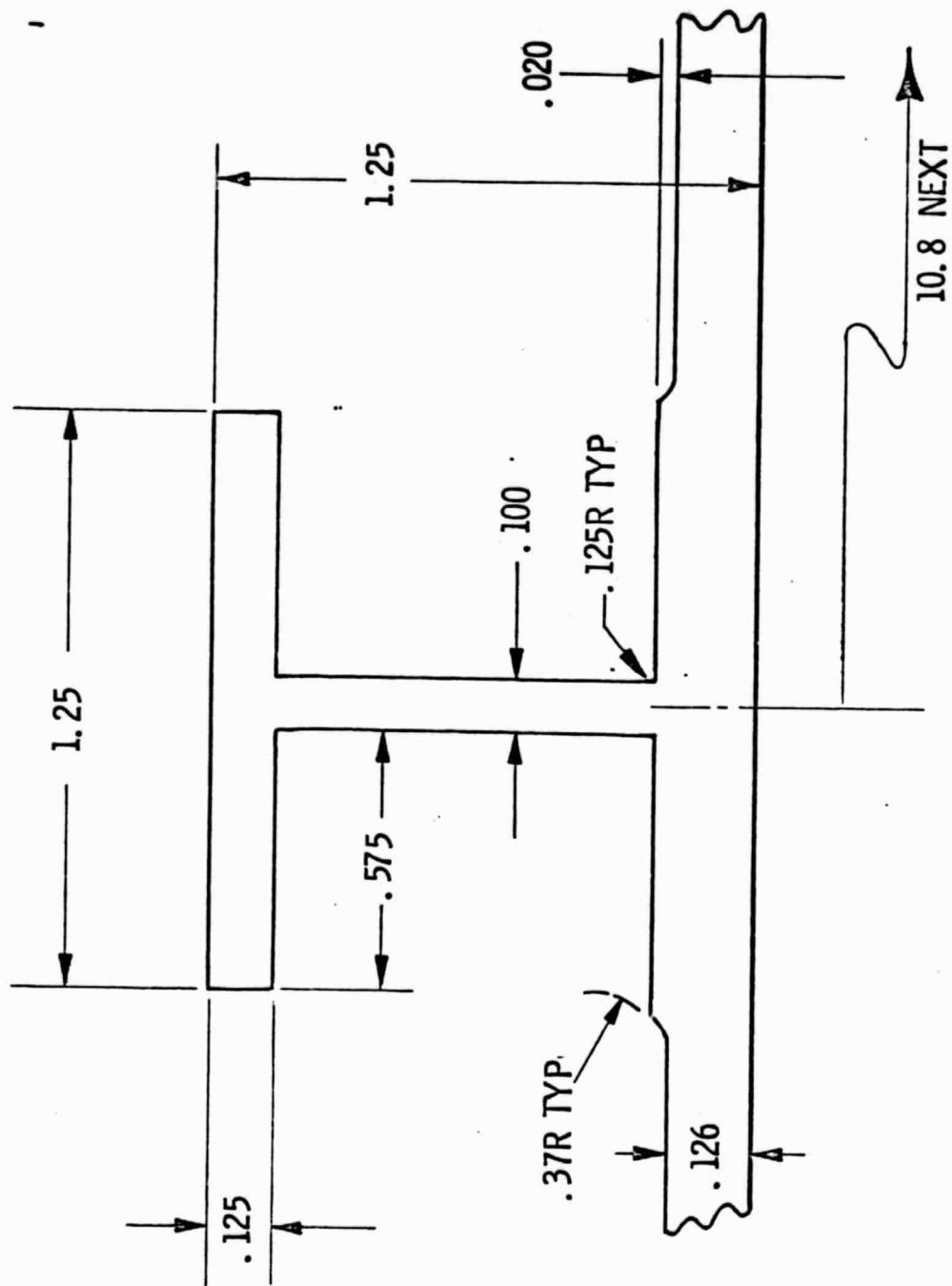


Figure 3-5. Section View of T-Rib Reinforcement of Fuel Tank Panel

Figures 3-6 and 3-7 show the 3-flute, 1-1/4 in. diameter end mill chosen as the roughing cutter to be used for removing the major portion of the pocket area between the T-ribs of the panel. The 3/8 in. corner radius end mill chosen for forming the 3/8 in. radii at the base of the T-ribs and for finishing the closed end of the panel is shown in Figures 3-8 and 3-9. This cutter has the same basic geometry as the roughing cutters except for the large radiused corners. Both 1-1/4 in. diameter cutters are made from ASP60 improved high speed steel.

The 4 in. diameter cutter chosen to cut the underside of the T-rib sections is shown in Figures 3-10 and 3-11. This cutter also had been previously used for high-speed machining aluminum. The corner radii of the teeth were increased to 0.125 in. to form the required fillets of the T-rib. The brazed inserts utilized in this cutter are made from Weldon Tantung, an alloy of tantalum and tungsten which is noted for its toughness.

Because of the required modifications of the cutters, the lack of experience in high-speed machining the 2219-T87 alloy, and the minimum time available on the Sundstrand OM4 NC machining center, cutter trials were conducted previous to the machining of the panels themselves. These trials were performed on a Sundstrand OM3 NC machining center (Figure 3-1) which was more readily available than the OM4. As the cutter trials were scheduled approximately one month in advance of the actual panel cutting demonstration, a safety period was thus provided during which further cutter modification could be accomplished if necessary. Furthermore, the cutter trials provided a means of testing the NC part program in advance.

Preparation for the cutter trials included the following activities. A somewhat reduced panel section which could be accommodated on the OM3 machining center was selected. The NC program was written. The cutters were modified and tool holders balanced. After the 18,000 rpm Bryant high-speed spindle motor was installed in the OM3, vibration tests were conducted to detect any resonant frequencies.

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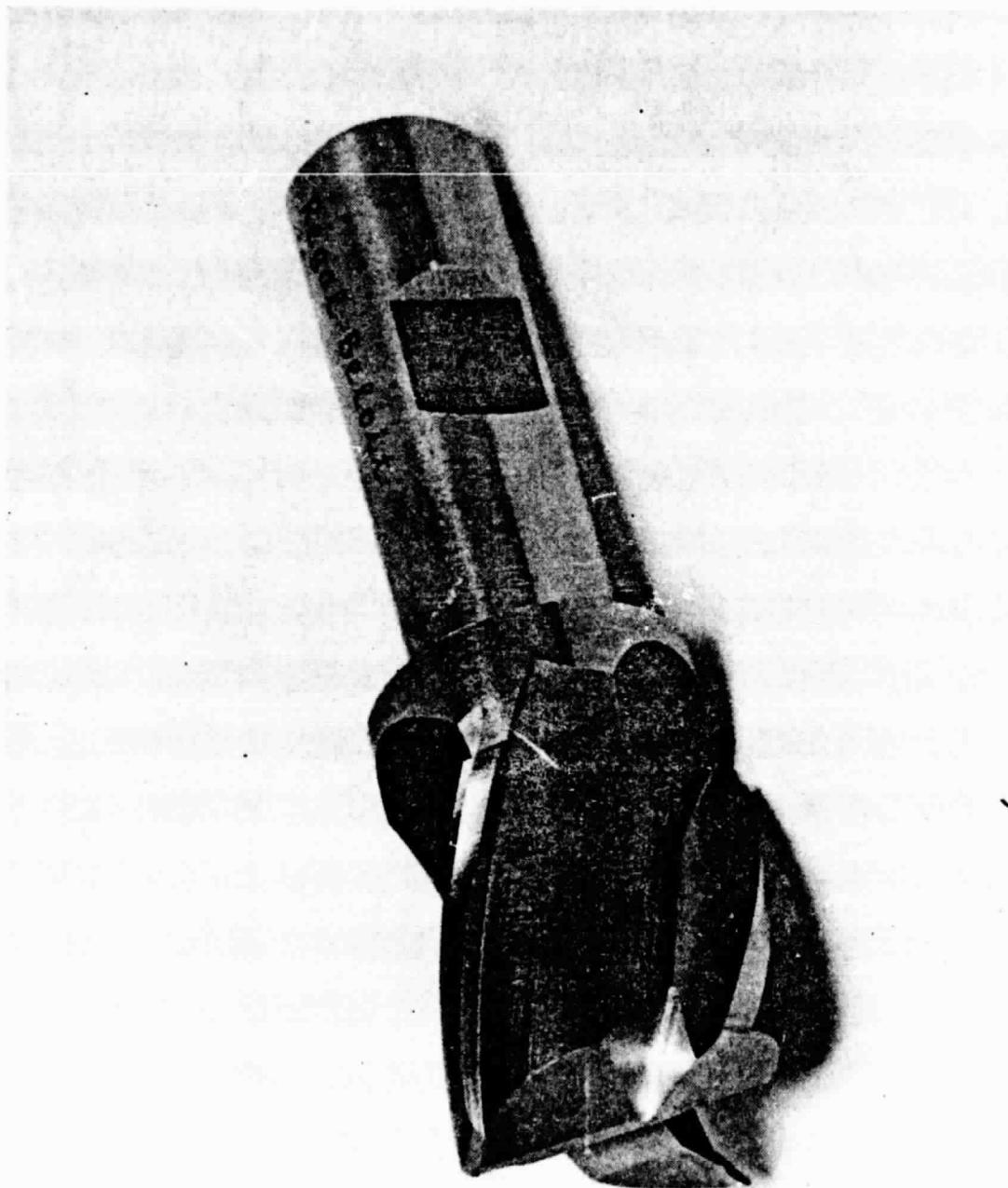


Figure 3-6 1-1/4 In. Diameter Three-Flute End Mill Selected as Roughing Cutter

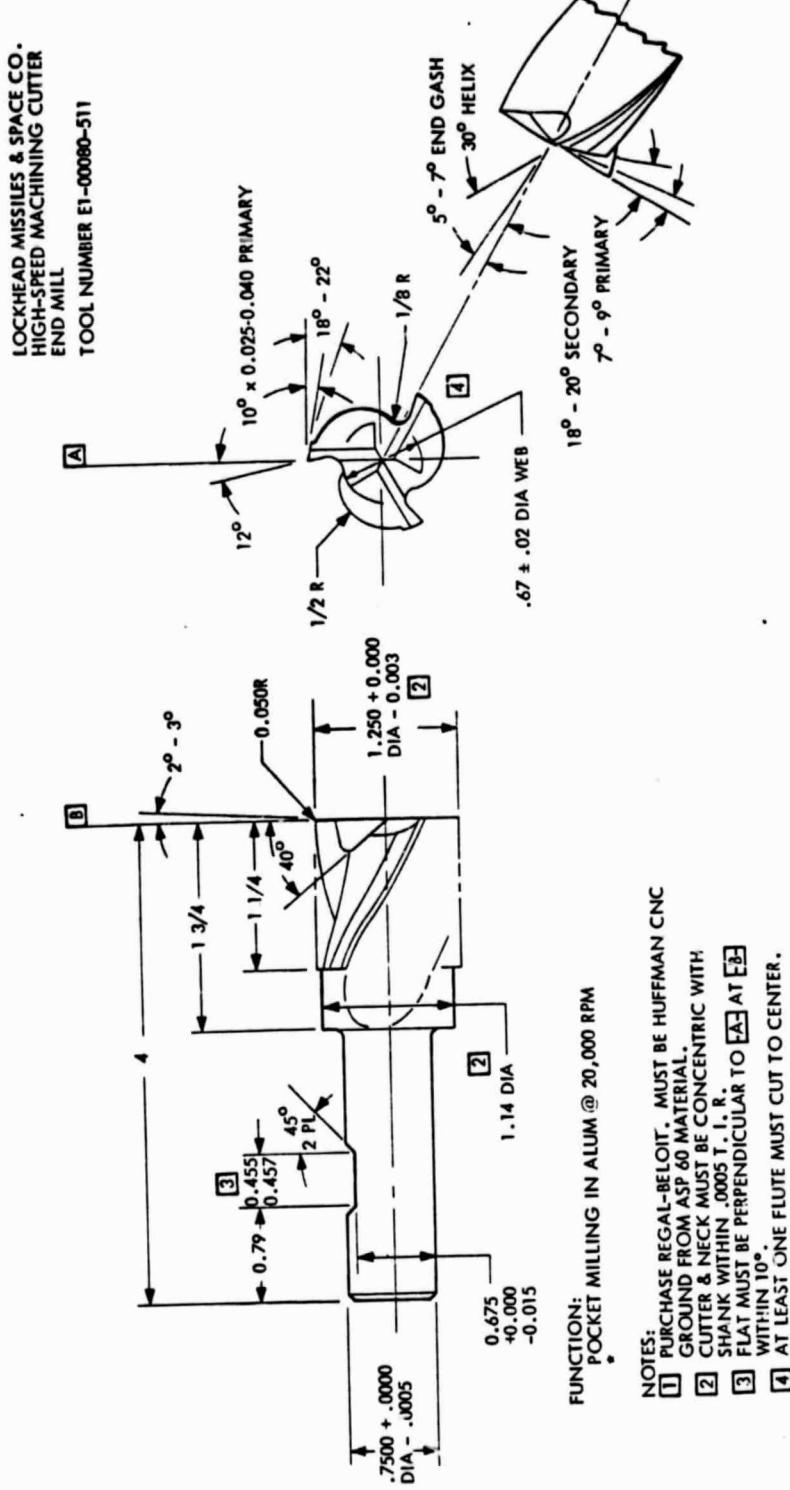
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Figure 3-7 Detailed Specifications for Roughing Cutter

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Figure 3-8 1-1/4 In. Diameter 3/8 In. Corner Radiused End Mill Selected as Finishing Cutter

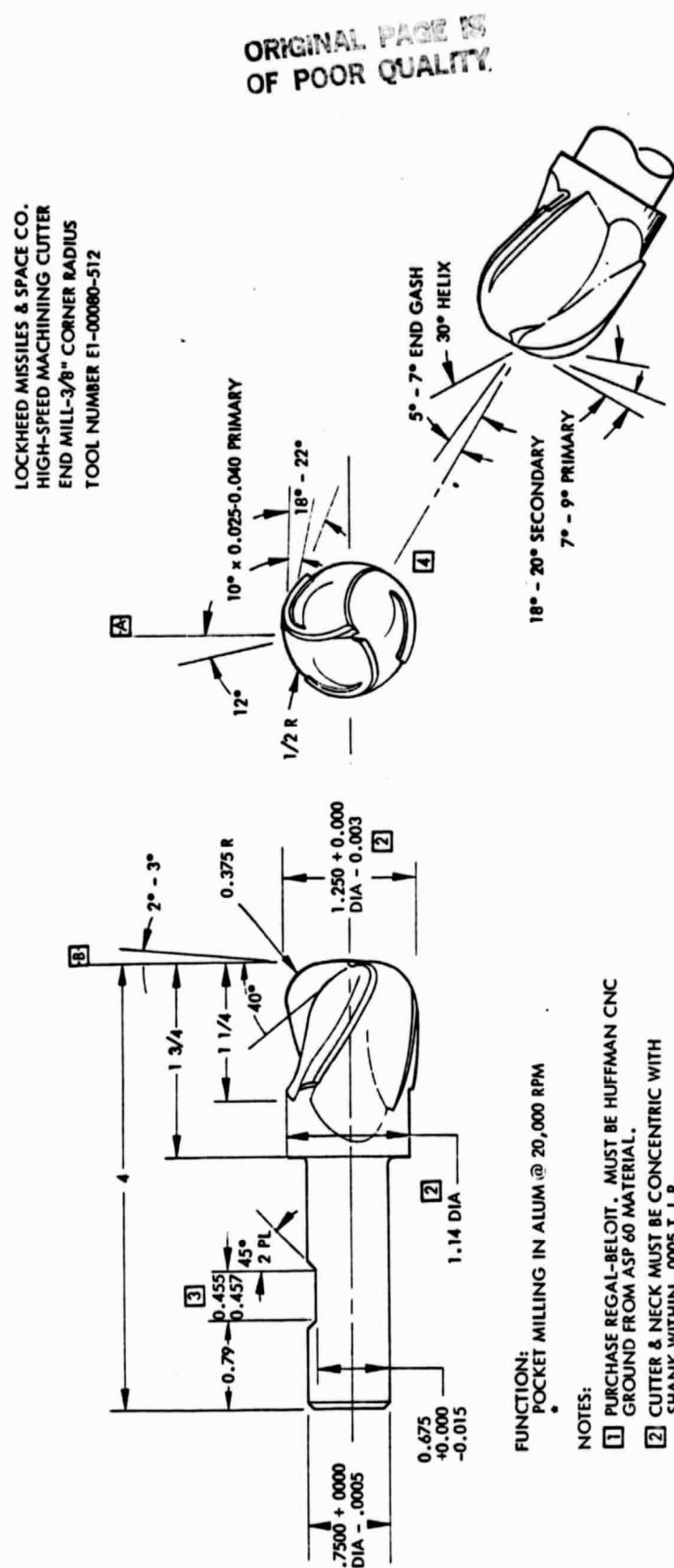


Figure 3-9 Detailed Specifications for Finishing Cutter

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Figure 3-10 4 In. Diameter Cutter Selected for Machining T-Rib Sections

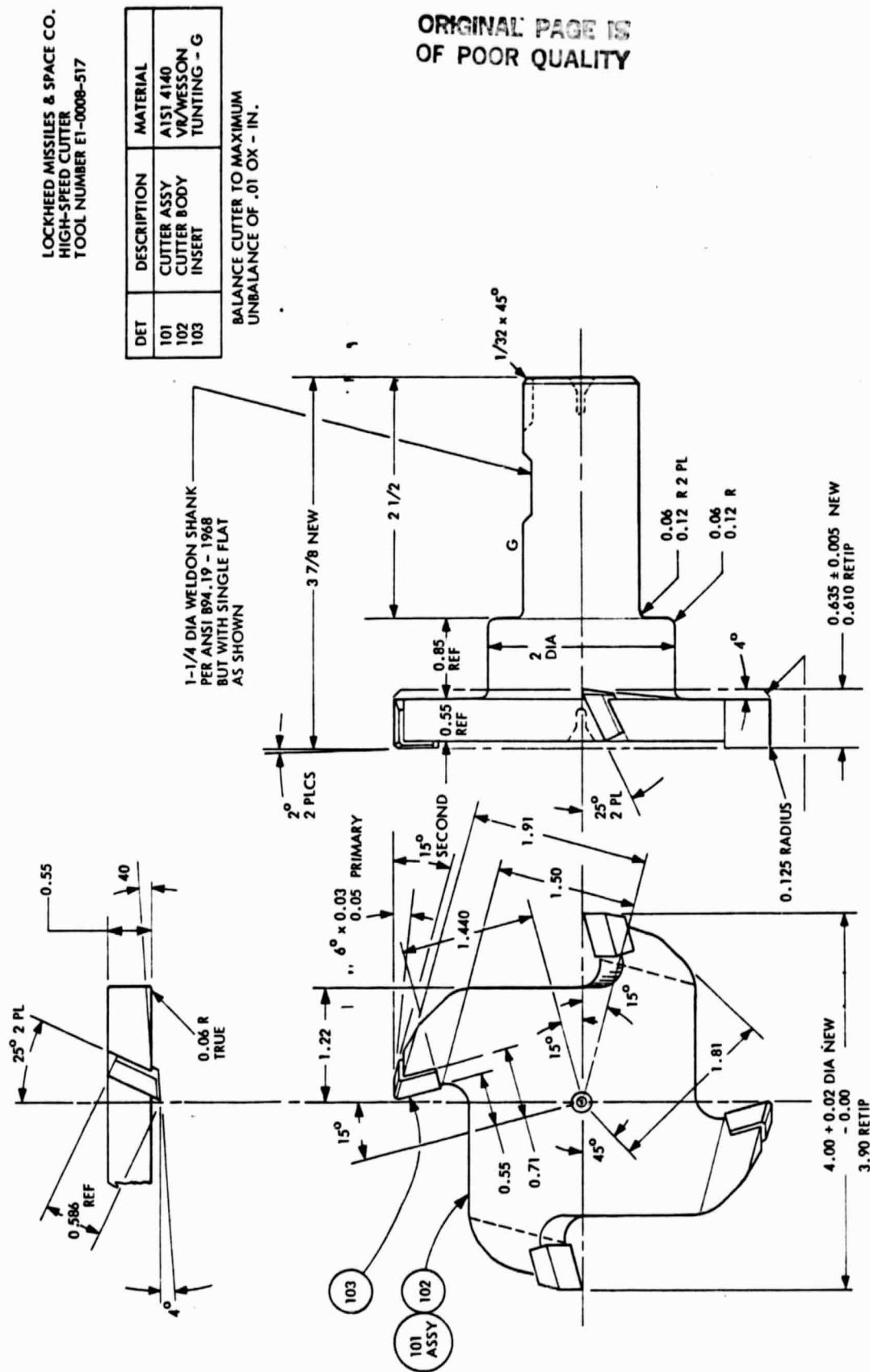


Figure 3-11 Detailed Specifications for T-Rib Cutter

Following the preparation steps, the cutter tests were run repeating the chosen pocketed section two times. As a result, each cutter received minor modification to provide additional chip clearances or room for the chips to clear the body of the cutter. A few minor adjustments were also made in the NC program, including the feeds and speeds, and the section was remachined the third time.

The resulting part was felt to be very satisfactory and, subsequently, planning was continued for the machining of the regular panel sections and the formal panel cutting demonstrations on the larger machine.

3-4 HIGH-SPEED MACHINING OF PANELS

3-4.1 Preparation

Preparing for the machining of the larger panel sections and converting the Sundstrand OM4 machining center for high-speed machining included several steps which are described below.

3-4.1.1 Panel Blanks - Identification and Premachining. The 2219-T87 wrought aluminum panel blanks as received from Martin Marietta were 2 in. thick and ink-stencilled with metal grain direction and both lot and individual panel identification numbers. To assure the maintenance and integrity of this information all the numbers were recorded and the individual panel numbers were steel stamped on three of the edges of each respective panel (See Appendix A for these numbers). The fourth edge was not stamped but ink-marked and then cut off to provide the 41 in. maximum width dimension that could be accommodated on the machining center. Care was taken to be certain that the grain flow was left in the longer direction of the panel thus guaranteeing that the grain direction in the finished panels would be parallel to the length of the T-ribs.

To ensure that the panel blanks would mount flat on the vacuum base plate, both sides were ground flat and parallel to each other. At the same time the blanks were reduced in thickness to the 1.75 in. specified by Martin Marietta drawings. Mounting bolt holes were provided around the perimeter on three sides of the panels.

3-4.1.2 Base Plate. To provide adequate backup and holding capabilities for the panels, a 2 in. thick aluminum vacuum chuck, or base plate, was decided upon. The base plate was designed, acquired, and prepared with vacuum grooves zoned in three separate areas to accommodate both the 4 ft. and 8 ft. long panels (See Figures 3-3, 3-4, and 3-12). Tapped mounting holes were also provided around the perimeter of the plate by which the panels were aligned and secured.

3-4.1.3 NC Program Preparation. The two numerical control machining centers used on the project were selected with similar controls to facilitate the expansion of the program utilized for the cutter trials to that of the full-sized panel sections. The use of the NC programming capabilities of Lockheed's CADAM system also helped in expanding both the width and length of the panels and in reprogramming the second half of each panel. The panels were programmed in halves to allow them to be indexed to produce 38-in. finished width panels on a machine which has only a 21-in. width capacity when machining in the flat position. Feeds, speeds, and other machining parameters were used which were in keeping with Lockheed's previous high-speed machining experience and the findings of the cutter trials.

3-4.1.4 Machining Center Set-Up. After the installation in the Sundstrand OM4 Omnimil of the Bryant 18,000 rpm high-speed spindle motor with its peripheral support equipment, spectrum analysis vibration tests were run. This was done to guard against attempting to operate in any spindle speed range where natural resonance vibration frequencies might occur and thus cause possible problems with the machining process or damage to the equipment. (See spectrum analysis data in Appendix B.)

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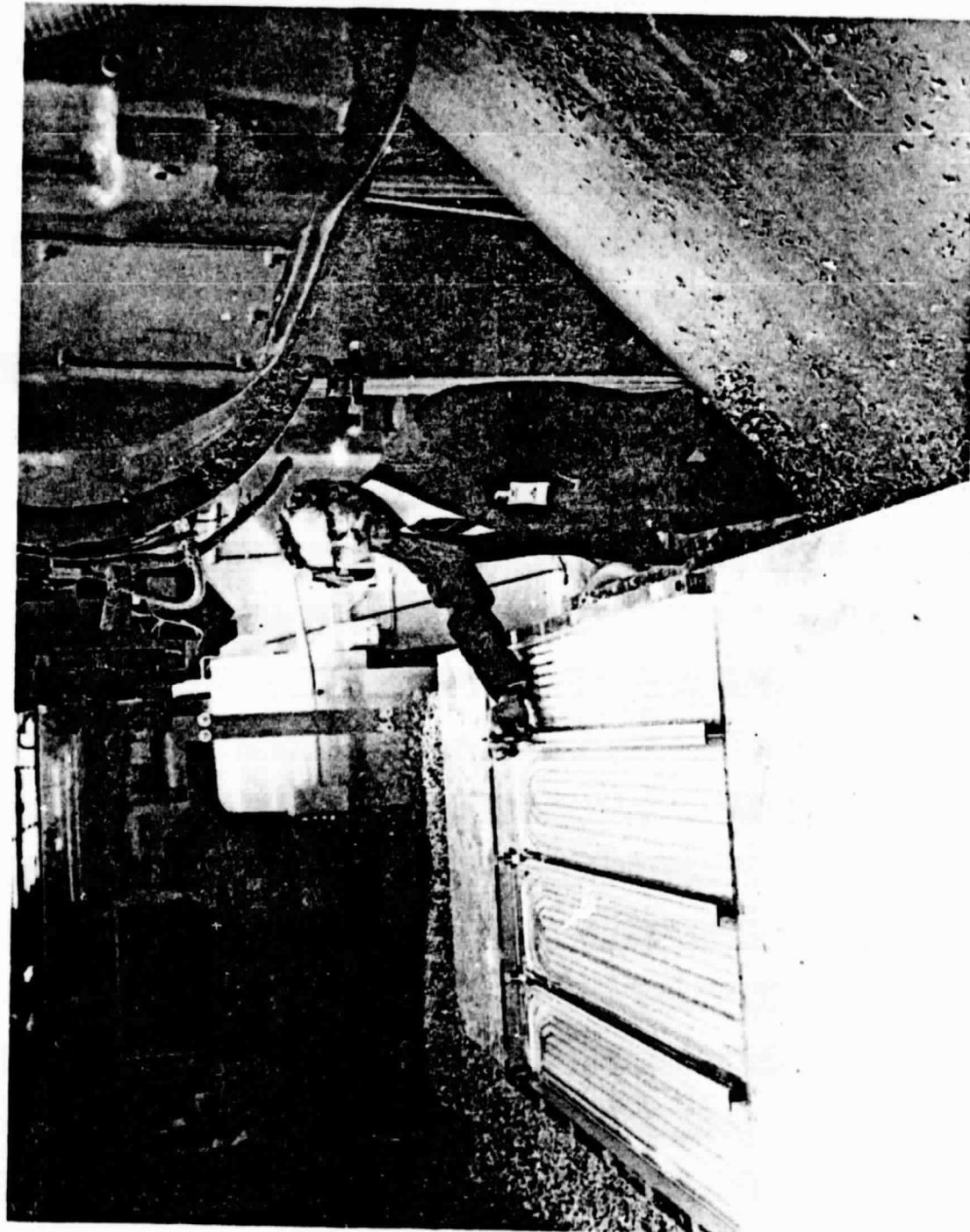


Figure 3-12 4 Ft Long Machined Panel on Vacuum Base Plate

Plastic Lexan shielding was mounted around the periphery of the machine table to provide safety protection for the machine operator and observers in the event of a tool breakage and also to provide containment for the flying chips and cutting fluid during machining. (See Figure 3-13.)

Two air nozzles were installed beside the spindle in addition to the two existing flood coolant nozzles to aid in keeping the chips out of the path of the cutter. In operation, the approach proved to be quite successful.

The base plate was next installed being properly aligned and secured to the machine table. This system including the vacuum feature also was later found to function very favorably.

3-4.2 Machining of First Panel

A 4 ft long panel was chosen for the first part to be high-speed machined on the OM4 machining center. The panel blank was first bolted in place and then sealed to the vacuum base plate with modelling clay. After the NC Program tapes were proofed by "dry running" on the machine, the panel was machined. (See Figure 3-12.) Following completion, the panel was shortened on the open end to provide small sections of T-ribs which were to be used as handouts during the scheduled panel cutting demonstration.

3-4.3 Panel Cutting Demonstration

The panel cutting demonstration was felt to be a major emphasis of this study. It was designed to demonstrate to NASA representatives and their invited guests the feasibility of utilizing high-speed machining as a means of producing the External Fuel Tank panels and thereby reducing manufacturing cost and time. These reductions were to be accomplished by increasing production rates and capacities and, in turn, reducing machine tool requirements.

The formal panel cutting demonstration was held on June 15, 1982 in Lockheed Building 181/182. Figure 3-13 is a photograph taken during the demonstration which shows the Sundstrand OM4 machining center on which the demonstration was performed and also some of the observers who were present. Formal attendees and the Lockheed crew are pictured in Figure 3-14. A list of attendees is provided in Appendix C.

The agenda (See Appendix D) included an introductory presentation which reviewed basic high-speed machining concepts as well as the objectives of the contract. Observation of the high-speed machining of a 4 Ft Long Shuttle Tank panel section followed.

A cutting speed of 5,890 surface feet per minute (sfpm) (over 60 miles per hour) was witnessed in the 1-1/4 in. diameter roughing and finishing cutters turning at 18,000 rpm. A table feed rate of up to 200 inches per minute (ipm) (the maximum capability of the machine) was observed as the roughing cutter removed up to 56 cu in./min of material while utilizing most of the maximum horsepower available (16.6) from the spindle motor.

The finishing cutter was fed at a rate of up to 180 ipm to remove up to 25 cu in./min of material. Rates up to 100 ipm table feed and 18 cu in./min were employed with the 4 in. diameter T-rib cutter which was operated at a cutting speed of 8,378 sfpm (8,000 rpm). Further detail is provided in Appendix E, "Setup and Operating Instructions for Machining 4 Ft Long Panels."

During the subsequent discussion period, NASA representatives emphasized their need for general specifications for a machine tool capable of high-speed machining the tank panels on a production basis. At least two attendees commented that because of the small size and tightly rolled shape of the chips produced by the high-speed machining process, they did not anticipate a problem with chip removal. Chip removal had been voiced previously as a serious concern.

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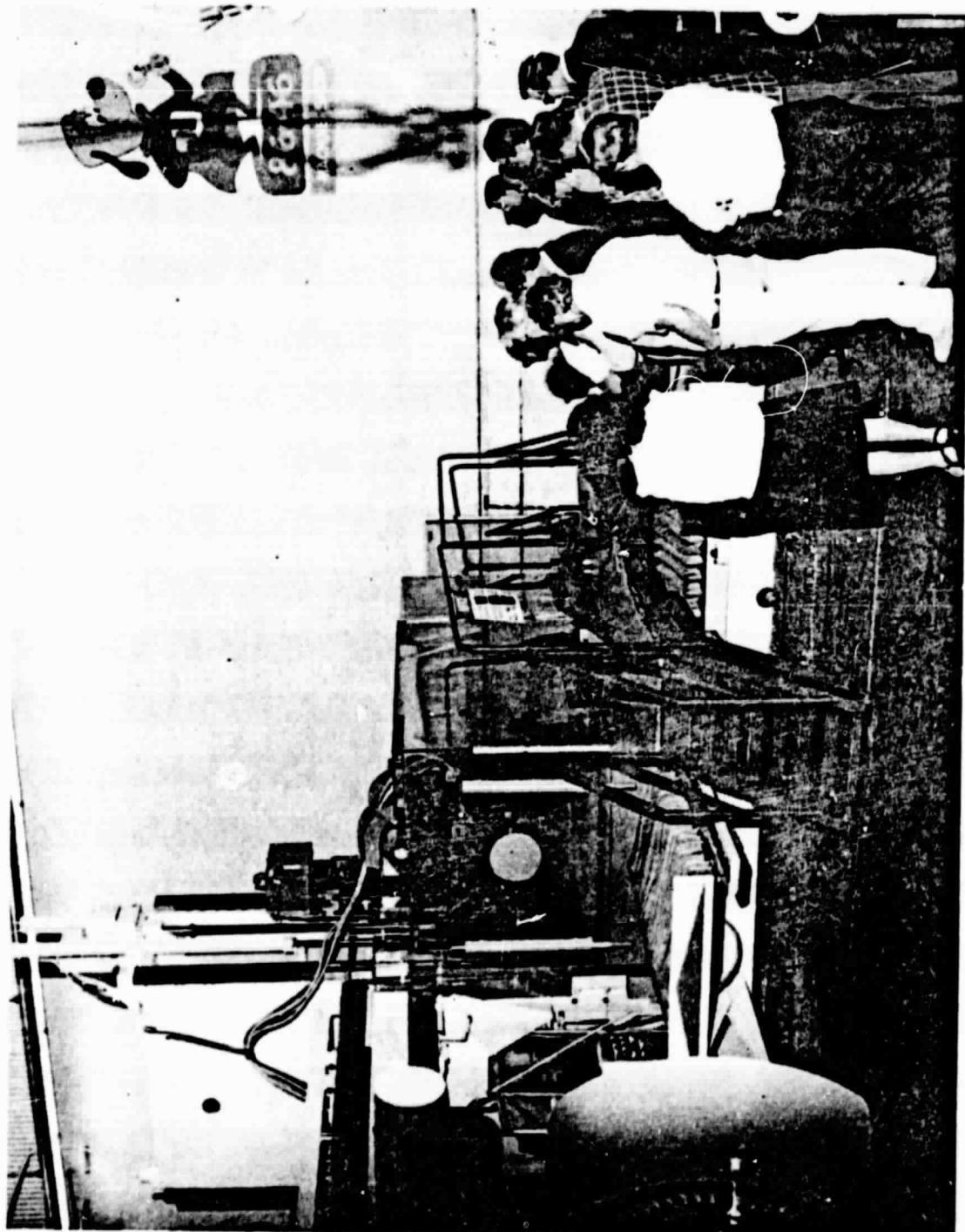


Figure 3-13 Observers at Panel Cutting Demonstration on Sundstrand OM4 NC Machining Center

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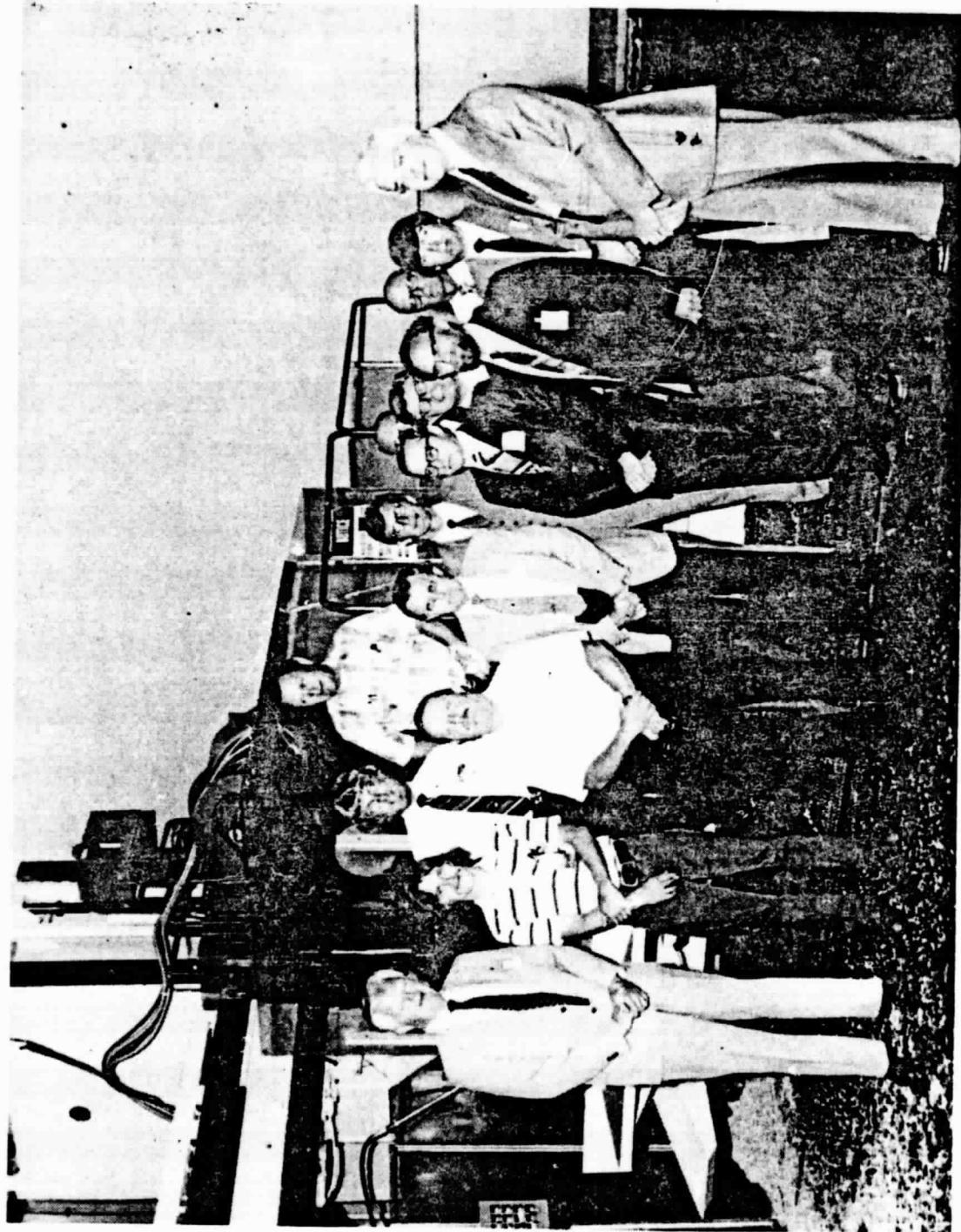


Figure 3-14 Attendees and Lockheed Crew at High-Speed Machining Panel Cutting Demonstration

3-4.4 Machining of Balance of Panels

Following the high-speed machining panel cutting demonstration, the balance of the deliverable panels (See Paragraph 2-1) was machined. A total of three 4 ft and one 8 ft long panels were completed. A video tape recording was made of the high-speed machining of the 8 ft long panel. Details of this effort are given in Section 4.

3-4.4.1 Recording of Horsepower. Actual horsepower utilized in making the various cuts was recorded (See Appendix F) for use in determining power requirements and in calculating cutting efficiency (See 6-1.).

3-4.5 Consideration of Cutter Wear

Particular attention was paid to cutter life (or wear) characteristics of the three cutter designs. Under proper conditions all three cutters showed excellent wear capabilities. Figure 3-15 is a photograph of the roughing cutter (See Figure 3-7 for detailed specifications.) which was used to perform the entire roughing of the 8-ft panel. The separate magnified views of the respective individual cutting edges shown in Figure 3-16 reveal only slight nicks (.002 in. max) at the tops of the utilized portions and at the height of the top of lesser depths of cut. The balance of the cutting edges show virtually no wear. The lighter area just back of the used portion of the cutting edges appears to be discoloration rather than noticeable wear. However, eventual crater wear would seem to be suggested.

The finishing cutter shown in Figure 3-17 was used for machining all four 4 ft long panels as well as the one 8 ft panel. No noticeable wear is seen in any of the views of this cutter. The detailed specifications for this cutter were given earlier in Figure 3-9.

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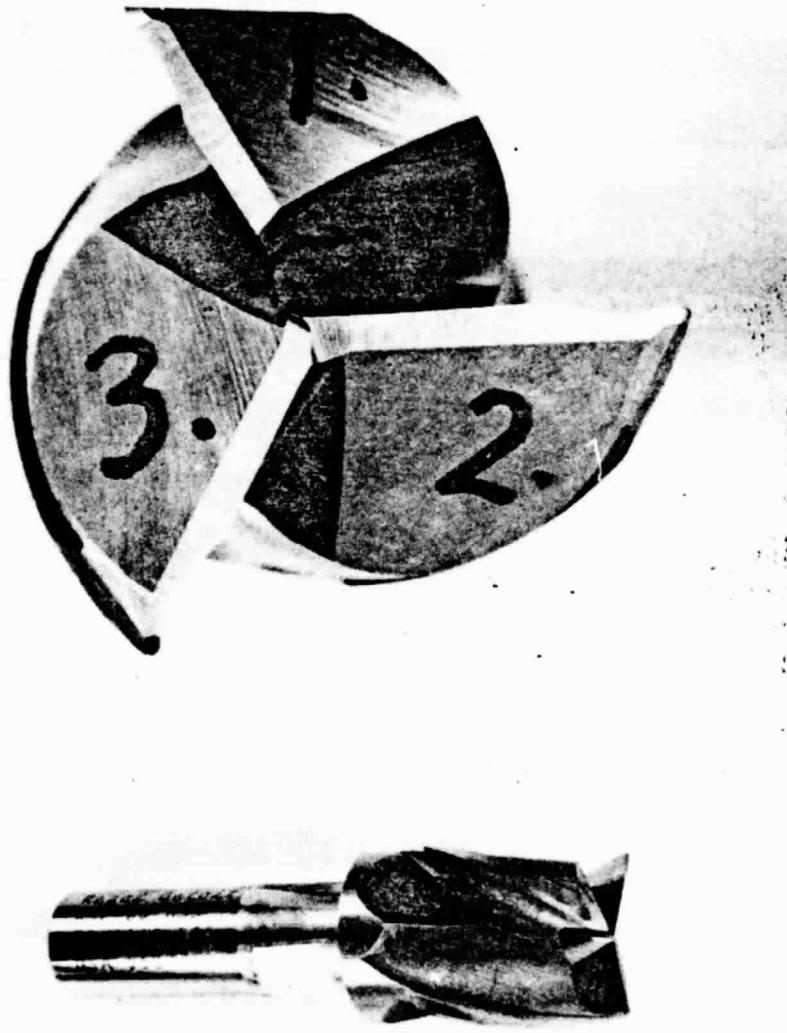
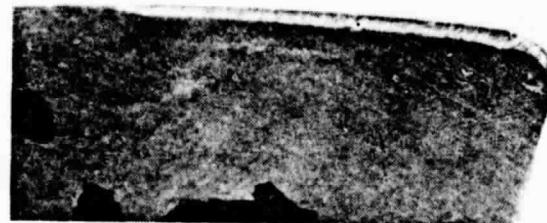


Figure 3-15 1-1/4 In. Diameter Roughing Cutter Used to Machine Entire 8 Ft Long Panel

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CUTTING EDGE NO. 1
CUTTING EDGE NO. 2
CUTTING EDGE NO. 3

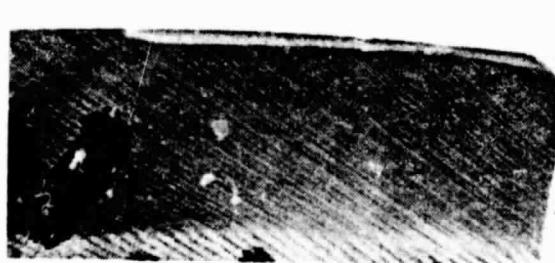
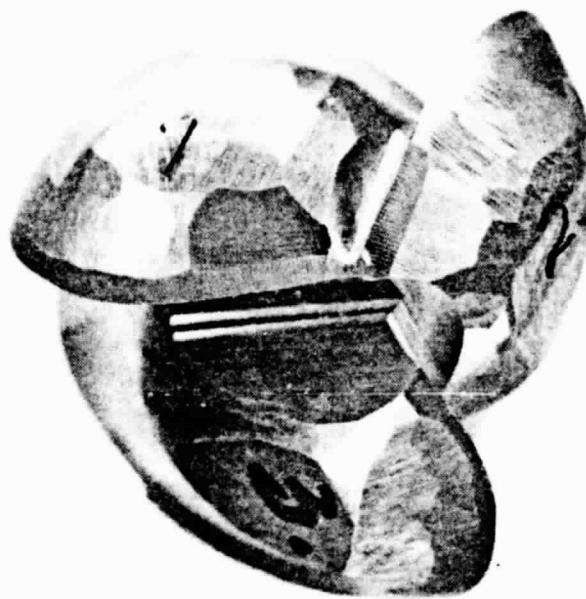


Figure 3-16 Cutting Edges of Roughing Cutter Used to Machine Entire 8 ft Long Panel
(Showing Only Slight Wear at 7 x Magnification)

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TYPICAL CUTTING EDGE
(APPROXIMATELY 7 x MAGNIFICATION)



(APPROXIMATELY 3 x MAGNIFICATION)



(REDUCED SIZE)

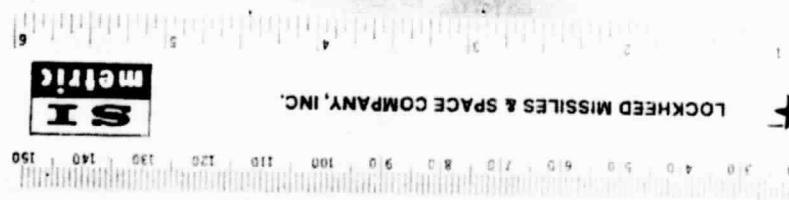


Figure 3-17 1-1/4 In. Diameter Finishing Cutter Used to Machine
All Deliverable Panels (Showing No Noticeable Wear)

Figure 3-18 pictures the T-rib cutter used for machining all five of the panels. As with the roughing cutter only a slight discoloration is shown behind the cutting edges of the inserts (See magnified views in Figure 3-19). No measurable wear is present.

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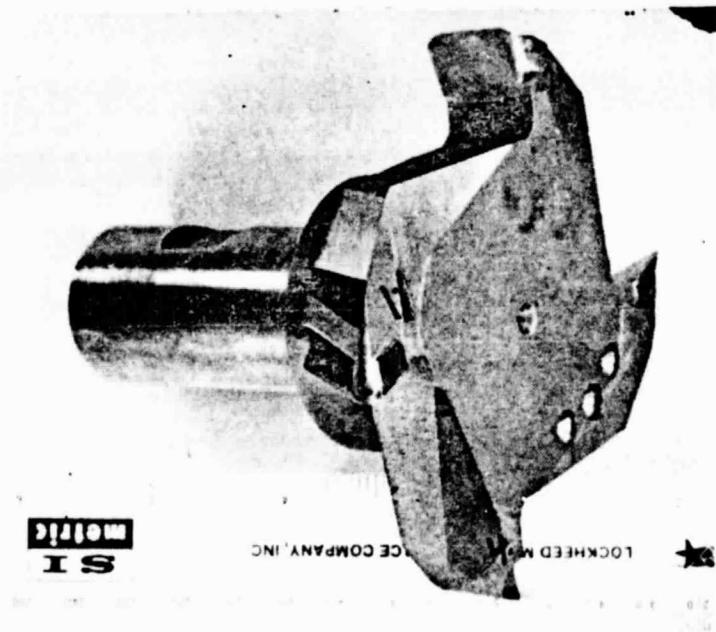
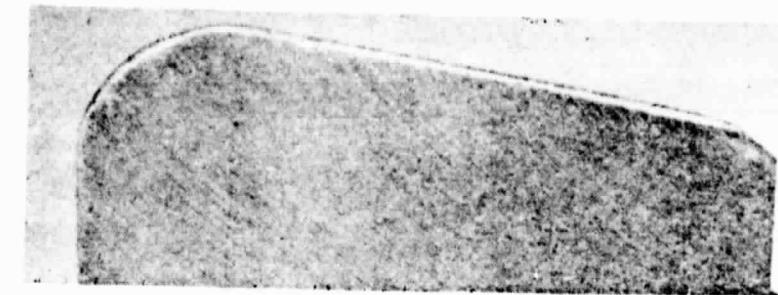


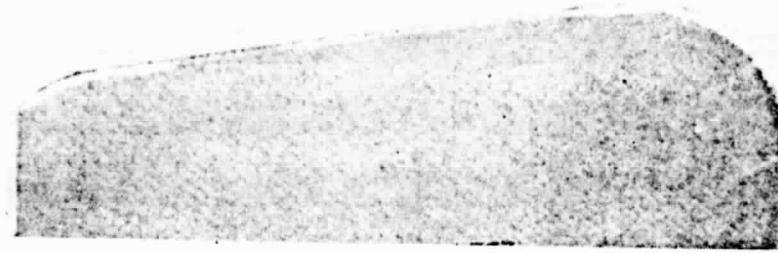
Figure 3-18 4 In. Diameter T-Rib Cutter Used to Machine All Deliverable Panels

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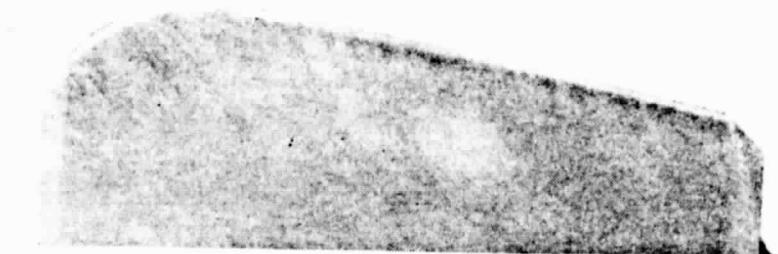
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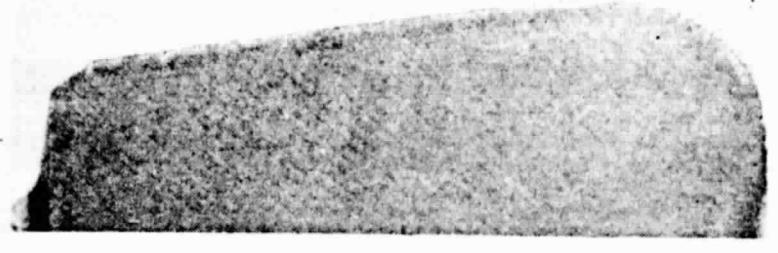
INSERT NO. 1



INSERT NO. 2



INSERT NO. 3



INSERT NO. 4

Figure 3-19 Insert Cutting Edges of T-Rib Cutter Used to Machine
All Deliverable Panels (Showing Negligible Wear at 7 x Magnification)

Section 4

VIDEO TAPING OF HIGH-SPEED MACHINING PANEL CUTTING PROCESS

As an addition to the original contract authorized by Change Order No. 3, the machining of the 8 ft long panel was video taped in color. After careful planning, a total of approximately 50 minutes of original footage was taken using four 15 minute 3/4 in. Umatic tape format cassettes. The original footage was rough edited down to 23 minutes by omitting repetitious scenes and other extraneous portions. Both the original footage and the rough edited versions were narrated in writing and mailed to the Marshall Space Flight Center.

Section 5

FINAL PREPARATION AND SHIPMENT OF DELIVERABLE ITEMS*

The 1-1/2 in. margins used for mounting during machining were removed from the panels in preparation for shipment. The identification numbers which had been steel-stamped on the edges of the panel blanks were carefully transferred to the backs of the finished panels. The panels were then hand deburred and chemically cleaned to avoid corrosion. Figure 5-1 and 5-2 are photographs of the finished 4 ft and 8 ft panels, respectively.

The three 4 ft long (identification numbers LS1, LS3, and LS4 - See Appendix A) and one 8 ft long (LL2) finished panels were properly crated and shipped with the two remaining 4 ft long (LS2 and LS5) and one 8 ft long (LL1) panel blanks to the Marshall Space Flight Center.**

The video tapes were also properly prepared and shipped to the Marshall Space Flight Center (See 4.0 for details.).

* See Section 2.1 for list of deliverable items.

** Note: The sixth 4 ft by 4 ft (LS6) panel blank had been used for the cutter trials.

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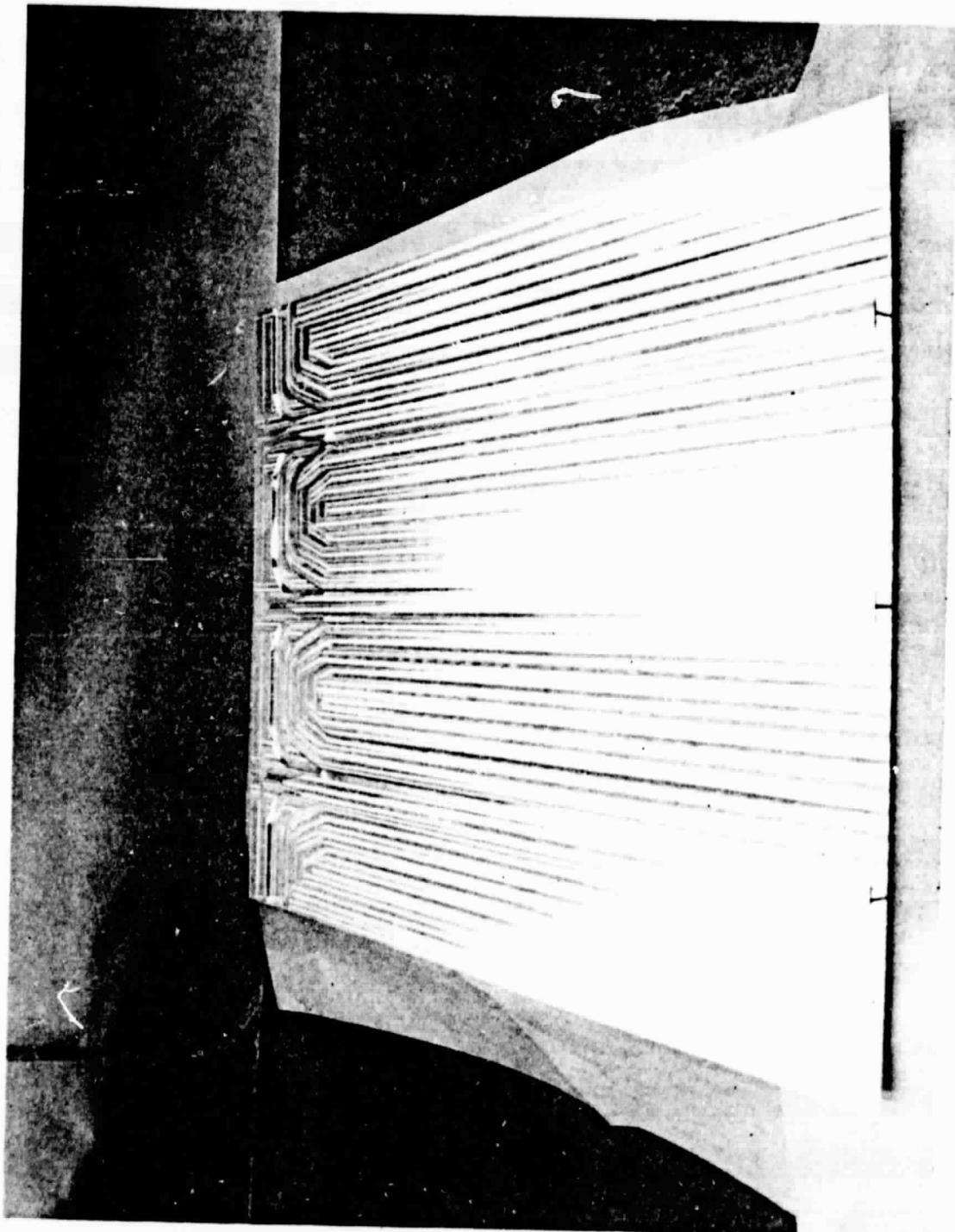


Figure 5-1 4 Ft Long Finished Panel

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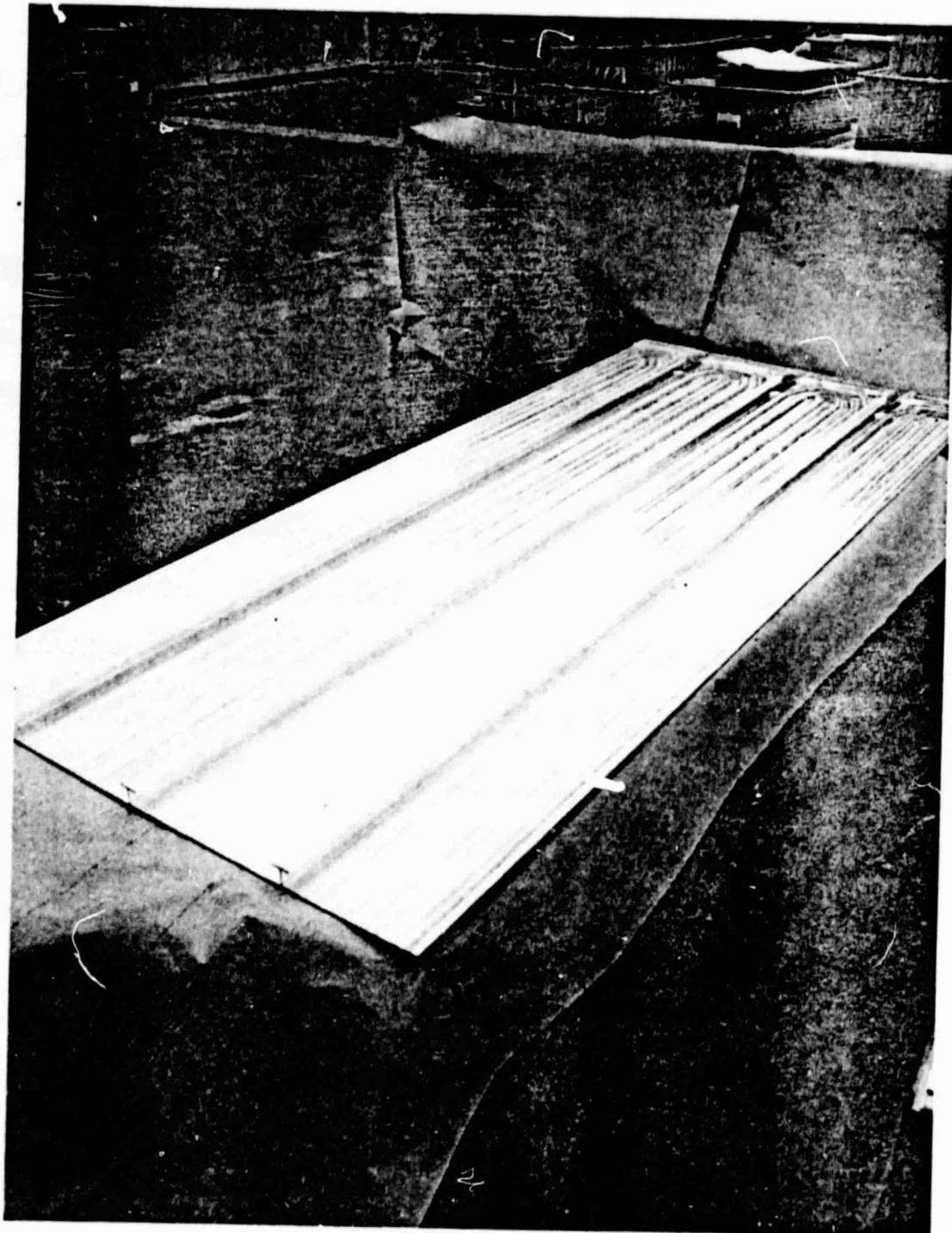


Figure 5-2 8 Ft Long Finished Panel

Section 6

HIGH-SPEED MILLING PROCEDURES AND TIMES *

The intent of this section is to identify the various high-speed machining process parameters, to describe the actual values of these parameters utilized in this project, and to identify optimum parameter values if different from those employed during the project. Times and operations involved in high-speed machining the Shuttle Tank panels will be stated and the time required to high-speed machine a complete panel will be projected.

6-1 DEFINITIONS AND ACTUAL VALUES OF HIGH-SPEED MACHINING PARAMETERS

The operations employed and the actual values of the various parameters used (See Table 6-1) are given below and in Appendix E, "Setup and Operating Instructions for High-Speed Machining of 4 ft Long Panels". The actual values are also given in Appendix F, "High-Speed Milling Data Sheet for 8 ft Long Panel #LL2." A compilation of these actual values is listed in Table 6-1.

6-1.1 Spindle Speed. Spindle speed is expressed in revolutions per minute (rpm) of the spindle or spindle motor. The spindle speeds used were 18,000 rpm for the 1-1/4 in. diameter roughing and finishing cutters (Figures 3-6 to 3-9) and 8,000 rpm for the 4 in diameter T-rib cutter (Figures 3-10 and 3-11).

6.1.2 Cutting Speed. Cutting speed when using a milling cutter is expressed as the peripheral speed of a cutter tooth tip stated as feet per minute (fpm) or surface feet per minute (sfpm). The cutting speed values employed in the high-speed machining of the tank panels were 5,890 sfpm for the 1-1/4 in. diameter cutters and 8,378 sfpm for the 4 in. diameter cutter.

* NOTE: This section was originally part of Task A but was transferred to Task B by direction of Change Order No. 1.

TABLE 6-1

ACTUAL AND PROJECTED PARAMETER VALUES FOR
HIGH-SPEED MACHINING TANK PANELS *

Parameter	Actual	Optimum	
		Proven Example: Cincinnati Milacron Gantry Mill	Available or Expected to be available soon
Spindle Speed (rpm)	18,000	7,200 (9,000 available from Cincinnati Milacron)	60,000 with 20hp 40,000 with 40hp 12,000 with 100hp
Cutting Speed (sfpm)	5,890	3,600	4,000 - 10,000 currently felt to be most efficient. (20,000 now used on large dia face mills etc.)
Table Feed (ipm)	200	150 (300 available from Cincinnati Milacron)	400 (1500 with 20hp)
Chip Load (in.)	.0032	.010	.010?
Depth of Cut Axial (in.)	.300	1.0	Dependent on hp available and dia of cutter (Shuttle panel limited to 1.625 in. maximum)
Radial (in.)	1.250	2.0	Dependent on dia of cutter and hp
Metal Removal Rate (cu in./min)	56	300 with 75hp	400 expected with 100hp (Up to 450 now using large dia face mills)
Horsepower	13.4	75 at 7200 rpm	100 at 12,000 rpm

(Cont'd)

TABLE 6-1 (Cont'd)

ACTUAL AND PROJECTED PARAMETER VALUES
FOR HIGH-SPEED MACHINING TANK PANELS *

Parameter	Actual	Optimum	
		Proven Example: Cincinnati Milacron Gantry Mill	Available or Expected To be available soon
Cutting Efficiency (cu in./min/hp)	4.0	4.0	?
(Unit hp-- hp/cu in./min)	0.25	0.25	?
Time to Machine 4 ft long Panel (hrs)	2.019		
Time to Machine 8 ft long Panel (hrs)	3.49		
Projected Time to Machine 11 ft x 20 ft Panel (hrs)	27.256 (Projected from 8 ft long Panel data)	6.0 (Base on Cincinnati Milacron data using hp) 5.1 (Based on maximum metal removal rates and adjusted using actual machining time)	4.48 (Based on inverse proportion of 100 hp vs time projected from 8 ft panel machine time)

* NOTE: These values are based on the maximum rates used for the roughing operation (Cutter No. 02). The blank panel is considered to be 1.75 in. thick and to have approximately 91% of the metal removed. Full-sized panels are considered to be 11 ft x 20 ft.

6-1.3 Table Feed. Table feed or feed rate when milling is the rate at which relative motion takes place between the machine table and the spindle, or head, of the machine. Table feed is expressed in inches per minute (ipm). Feed rates ranging from 150 to 200 ipm (the maximum capability of the machine) were used for the 1-1/4 in. diameter roughing and finishing cutters, and from 40 to 100 ipm for the 4 in. diameter T-rib cutter.

6-1.4 Chip Load. Chip load is the amount of metal that each flute or cutting edge removes as the cutter turns through one revolution as the workpiece is fed against it. Chip load is also called chip per tooth or feed per tooth and is expressed in inches (in). The chip loads utilized in high-speed machining the panels ranged from .0025 to .0032 in. for the roughing cutter, stayed constant at .0032 in. for the finishing cutter, and extended from .0016 to .0032 in. for the T-rib cutter. These relatively small chip loads helped to achieve the fine surface finish required by the part.

6-1.5 Depth of Cut. There are actually two types of depth of cut involved in milling. One is defined as axial depth of cut which is parallel to the centerline of the spindle. The other is called radial depth of cut and is perpendicular to the centerline of the spindle and cutter.

For the roughing cutter the axial depths of cut ran from .070 to .300 in. depending on how the levels, or layers, of cutter passes were divided. The radial depths, or widths, of cut ranged from 1.1 to 1.250 in., the full diameter of the cutter. The finishing cutter with the 3/8 in. corner radius was used primarily to provide the .370 fillet radius of the part. Therefore, both axial and radial depths of .370 in. were used. Axial depths from .075 to .635 in. and radial depths from .025 to .550 in. were utilized with the T-rib cutter.

6-1.6 Metal Removal Rate. This parameter is usually expressed in terms of cubic inches per minute (cu in./min) of metal removed. The values obtained were from 18 to 56 cu in./min (approximately 3X the comparable conventional machining rate at Lockheed) with the roughing cutter, to 25 cu in./min with the finishing cutter, to 18 cu in./min with the T-rib cutter. The two primary limiting factors in this case were horsepower and table feed.

6-1.7 Horsepower. Available power, or horsepower, to turn the cutter is the most limiting parameter where larger volumes of metal are to be removed, as with the tank panels. The Bryant 18,000 rpm spindle motor is rated at 16.6 hp at the full 18,000 rpm. Horsepower readings as recorded in Appendix F, "High-speed Milling Data Sheet for 8 ft Long Panel No. LL2", ran at approximately 13.4 hp for the roughing cutter for most of the cuts. Occasional peak loads ran momentarily higher. For Tool No.03, the finishing cutter, the loads ran at approximately 8.4 hp. The relatively light loads used with the T-rib cutter (Tool No. 04) drew a maximum of approximately 5.1 hp which was almost at the 5.5 hp maximum available at 8,000 rpm at which the spindle was operating.

6-1.8 Cutting Efficiency. Cutting efficiency is often expressed as cubic inches per minute per horsepower (cu in./min/hp). Using the values already cited in 6-1.6 and 6-1.7 to calculate cutting efficiency for the maximum metal removal rate, we find that 56 cu in./min divided by 13.4 hp yields a cutting efficiency of 4.18 cu in./min/hp. This value compares very favorably with the figure of 3.0 cu in./min/hp which is felt to be a somewhat conservative number for high-speed milling of aluminum.

Cutting efficiency is the mathematical reciprocal of unit horsepower which is expressed as horsepower per cubic inch of metal removed per minute. The unit horsepower equivalent to the 3.0 cu in./min/hp given above is 0.33 hp/cu in./min.

6-1.9 Time to Machine 4 ft Long Panel Section. The actual machining, or chip cutting time for high-speed machining the 4 ft long panel sections is presented in Table 6-1. The 2.019 hrs listed is the time generated by the NC program and found to be reasonably accurate in actual operation. This time does not include such activities as part loading and unloading and tool changes.

6-1.10 Time to Machine 8 ft Long Panel Section. As with the 4 ft long panel, the 3.49 hrs listed in Table 6-1 as actual time for high-speed machining the 8 ft long panel was generated by the Lockheed NC program. This computer calculated time was also found to be reasonably accurate.

6-2 PROJECTED TIME TO MACHINE FULL-SIZED 11 FT X 20 FT TANK PANEL BASED ON ACTUAL PROJECT DATA

The NC program cutter paths and times for high-speed machining the 8 ft long panel section were meticulously expanded to project a cutting time required to machine the entire full-sized 11 ft x 20 ft panel from which the sample section was taken. The total estimated time (as given in Table 6-1) is 27.2567 hrs. As only 13.4 hp was employed in machining the 8 ft sample panel, it became very apparent that horsepower was the greatest limiting factor, especially in the roughing operation at which over 80 percent of the time was spent. Obviously, even though the demonstration panel sections were high-speed machined very successfully and convincingly, the rates attainable on the available Lockheed equipment were not optimal for machining full-sized tank panels.

6-3 PROJECTIONS OF OPTIMUM HIGH-SPEED MACHINING PARAMETERS AND TIMES

High-speed machining is presently in a dynamic state of development. Therefore, projections of what appear to be "optimum" parameter values today may not be optimum tomorrow. In an attempt to deal with this rapidly changing situation, two sets of optimum parameter values are presented in Table 6-1 in addition to the "actual" values utilized during this demonstration project.

6-3.1 Projections Based on Proven Data. The first set of optimum parameter values projected for high-speed machining Shuttle External Fuel Tank panels is based on proven data given as an example. This data was made available by Cincinnati Milacron * and is presented to emphasize that equipment capable of providing the high-speed machining parameter values listed in Table 6-1 is readily available today.

* T. Raj. Aggarwal. Research in Practical Aspects of High Speed Milling of Aluminum. Presented at the SME Annual International Tool and Manufacturing Engineering Conference, Philadelphia, PA, May 17, 1982.
(NOTE: T. Raj Aggarwal is an R&D Associate at Cincinnati Milacron).

As presented in Table 6-1, the impressive volume of 300 cu in./min of metal removed by Cincinnati Milacron was achieved using a 75 hp spindle turning a 2 in. diameter end mill at 7200 rpm. The surface finish resulting from the relatively heavy chip load of .010 in. and cutting speed of only 3,600 sfpm, no doubt, was acceptable for a roughing operation. However, to produce less tool side pressure and better surface finish which would likely be required for the T-rib sections of the tank panels, higher cutting speeds would probably be required. The higher cutting speeds could be achieved by either increasing the diameter of the cutter while keeping the rpm constant or by increasing the rpm with the same diameter cutter. In either event, a table feed faster than the 150 ipm cited in the example would be in order to be able to maintain a proper chip load.

Using the high-speed machining parameter values available as shown in this example, the projected time to machine a full-sized 11 ft x 20 ft panel was computed by two methods. Both projection methods yielded impressively less time than predicted from the 8 ft panel cutting data.

First, horsepower was used as a predictor as it had been found to be the dominant limiting factor in our Lockheed panel cutting operations. It was determined that cutting time could be expressed as being in a direct but inverse relationship to available horsepower. Based on a machining time of 27 hrs required by the 16.6 hp spindle motor used, it was determined that a 75 hp motor should be able to accomplish the same job in approximately 6.0 hrs.

The second method employed to predict cutting time for a full-sized panel was based on the computed volume of metal to be removed and the maximum metal removal rate for each of the spindles being compared. Using an estimated volume of 50,182 cu in. of metal to be removed, the 16.6 hp Lockheed spindle with a maximum metal removal rate of 56 cu in./min could be expected to machine the full panel in 14.9 hours. However, the actual projected NC program time to machine the panel using the 16.6 hp spindle was 27.3 hrs (See Table 6-1). Therefore, an adjustment factor of 1.83 was computed by dividing the 27.3 actual projected hours by the 14.9 calculated hours. By adjusting the 2.8 hrs calculated for the 75 hp spindle by this 1.83 factor, a more logical

projected machining time of 5.1 hrs was determined. As noted above, either of these projected machining times would suggest considerable potential savings in machining time.

6-3.2 Projections Based on Capabilities Which are Available or are Expected to Be Available Soon. The second set of optimum parameter values projected for high-speed machining Shuttle External Fuel Tank panels is a compilation of information from various sources. Most of these capabilities are available singly now. However, the exact combination of all "optimum" parameter values desirable for high-speed machining Shuttle Tank panels has probably not yet been assembled.

As horsepower was determined to be the most critical limiting parameter for the high-speed machining of parts requiring relatively large amounts of material to be removed, including Shuttle Tank panels, the "optimum machine" would most likely be fitted with as large a horsepower motor as possible. The 100 hp, 12,000 rpm spindle motor listed in Table 6-1 is the largest known to the author which has been conceived specifically for high-speed machining. Although this motor has not yet been built, the technology required is reportedly available and proven. If such a motor were capable of operating at a cutting efficiency of 4.0 as was demonstrated during the Lockheed panel cutting demonstration and claimed by Cincinnati Milacron in the example cited in Table 6-1, it would be able to remove 400 cu in./min. This would equate to a 2.5 in. dia cutter cutting at 1.624 in. deep (the maximum possible depth of cut required for machining a 0.126 in. panel skin from a 1.75 in. blank) at a table feed of 98.5 ipm. Since the cross-sectional area of 2.5 in. x 1.624 in. = 4.06 sq. in. essentially an entire pocket between T-ribs could be machined out in four passes at approximately 100 ipm. For finish machining the radii and for machining the T-rib sections, the cross-sectional area of metal to be removed per pass would be considerably less. Therefore, available table feeds should be higher in proportion to maintain as high a volume of metal removal as possible. As 300 ipm table feeds are available now for gantry-type machines such as would be expected to be used for machining tank panels, it is logical to expect that 400 ipm table feeds are either also available now or will be in

the near future. Reportedly, one company has built a light duty gantry-type machine with a table travel capability of 1500 ipm.

Faster feed rates also require higher rpm to keep the chip/tooth loads light enough to minimize side loads on the T-rib sections and provide sufficient surface finish. The smaller the diameter of cutter used, the higher the rpm will need to be. Presently the bearings for relatively large horsepower motors are the limiting factors in increasing the rpm above approximately 9,000 to 12,000. For this primary reason, some manufacturers of high-speed spindles are developing magnetic bearings. To date, the author is not aware of any proven magnetic bearing spindles with the horsepower level recommended for machining tank panels.

A projected time to high-speed machine a full-sized tank panel was calculated based on the 100 hp, 12,000 rpm spindle. A value of 4.48 hrs was determined based on an inverse proportion using the 100 hp and the 27.3 hrs projected from the 8 ft long panel data. This represents an additional 25 percent reduction in time from the 6.0 hrs predicted for the 75 hp spindle. The assumptions of a continued cutting efficiency figure of 4.0 cu in./min/hp and the maximum metal removal rates used in the projections should be kept in mind.

SECTION 7
SUMMARY AND CONCLUSIONS

7-1 SUMMARY

Lockheed Missiles & Space Company, Inc. contracted with the NASA Marshall Space Flight Center in Huntsville, Alabama to provide certain technical services for the purpose of evaluating the flexibility of applying high-speed machining techniques to the milling of Space Shuttle External Fuel Tank panels. The contract was divided into two main categories or tasks. Task A was designed to document and evaluate the parameters currently involved in conventionally machining the Shuttle Tank panels and to compare them with equivalent high-speed machining parameters. An economic analysis was to be made projecting expected savings in machining costs from the comparison. This document reports Task B activities which are summarized below.

Task B was primarily designed to demonstrate the applicability and advantages of high-speed machining for producing Shuttle Tank panels by physically machining selected sample portions of an external tank panel. Lockheed was asked to show that the high-speed machining techniques and technical expertise employed in machining missile hardware could be transferred to the production of Shuttle Tank panels. Actual data from the high-speed machining of the sample panel sections were to be used to project the anticipated time for high-speed machining an entire Shuttle Tank panel using optimal equipment.

Specific Task B tasks were as follows:

- 1) Select a panel sample configuration
- 2) Perform a high-speed machining demonstration and machine additional panels
- 3) Prepare a Task B final report.

Through change orders the following tasks were added.

- 4) Machine an 8 ft long panel section
- 5) Incorporate the paragraph from Task A entitled "Identify Potential High-Speed Milling Procedures" including projections for using optimal equipment into Task B
- 6) Video tape the high-speed machining process.

The above tasks were successfully completed within budget, on schedule (as adjusted), and with all goals and specific technical objectives achieved.

The sample panel configuration was selected in accordance with Marshall Space Flight Center requirements and within the limitations of Lockheed's available equipment. Three cutter designs were selected based on the requirements of the part and on Lockheed's background in the high-speed machining of aluminum. After selection the cutters were tested on a sample part.

A Sundstrand OM4 Omnimil NC Machining Center was retrofitted with an 18,000 rpm Bryant spindle motor to machine the panels and perform the demonstration for NASA representatives and their invited guests. During the high-speed machining of the panels the various parameters involved were monitored and recorded. The spindle was operated at 8,000 and 18,000 rpm yielding cutting speeds of 5,890 and 8,378 surface feet per minute (sfpm).

Table feeds of up to 200 in./min (ipm) (the maximum capacity of the machine) producing metal removal rates up to 56 cu in./min (approximately 3x the comparable conventional machining rate at Lockheed) were employed.

From the data generated during the actual panel machining, projections were made to optimum rates which could be expected to be achieved if ideal equipment were available for machining full-sized Shuttle Tank panels. A video tape record was made of the machining of the 8 ft long panel.

CONCLUSIONS

In conclusion, the high-speed machining techniques utilized in Lockheed's missile production were successfully transferred to the manufacture of portions of Shuttle External Tank panels.

Furthermore, it was projected that with properly designed equipment, metal removal rates up to 300 cu in./min could be achieved and an entire Shuttle Tank panel could be high-speed machined from a 1.75 in. thick solid panel in as little as 6.0 hrs using equipment known to be available today. Even less time was projected using equipment for which technology to build is now available.

APPENDICES

- Appendix A IDENTIFICATION NUMBERS OF SHUTTLE TANK PANEL BLANKS
- Appendix B SPECTRUM ANALYSIS OF OM3-3 AND OM4B
- Appendix C ATTENDEES AT PANEL CUTTING DEMONSTRATION
- Appendix D AGENDA FOR PANEL CUTTING DEMONSTRATION
- Appendix E SETUP AND OPERATING INSTRUCTIONS FOR HIGH-SPEED MACHINING 4 FT LONG PANELS
- Appendix F HIGH-SPEED MILLING DATA SHEET FOR 8 FT LONG PANEL No. LL2

APPENDIX A

IDENTIFICATION NUMBERS OF SHUTTLE TANK PANEL BLANKS

4 FT BY 4 FT PANELS

LS1

RS9-790460 MMS118M771
LOT CODE AWG LOT-269-211, 273-511
255-331, 273-521-269-221 *

DATE 7/28/79 TRACEABLE

LS2

(Only partial stencilling)
RS9-7904

DATE 7/28/79 TRACEABLE

LS3

RS9-790460 MMS118M771 RTR-106
LOT CODE AWG LOT-269-211, 273-511
255-331, 273-521-269-221

DATE 7/28/79 TRACEABLE

LS4

RS9-790460 MMS118M771 RTR-106
LOT CODE AWG LOT-269-211, 273-511
255-331, 273-521-269-221

DATE 7/28/79 TRACEABLE

LS5

(No stencilled marks on edges)

LS6

(No stencilled marks on edges)

* The lot number 269-221 is the only lot number stencilled on the panel blanks that was excluded from the list of lot numbers provided by Martin Marietta in a letter dated January 22, 1982 from Gerry Scott to Dr. R.I. King of Lockheed. Also, the lot number 273-512, listed in Mr. Scott's letter, was not stencilled on any of the panel blanks.

APPENDIX A

4 FT BY 8 FT PANELS

LL1

RS9-790460 MMS1118M771 RTR-106
LOT CODE AWG LOT-269-211, 273-511
255-331, 273-521-269-221

(No Date)

LL2

RS9-790460 MMS1118M771 RTR-106
LOT CODE AWG LOT-269-211, 273-511,
255-331, 273-521-269-221

DATE 7/28/79 TRACEABLE

NOTE: LS and LL numbers were steel-stamped midway on 3 edges
of each part. The stamp was omitted on the edge to be cut
off to narrow the panels to 41 in.

APPENDIX B

LMSC-D880308

LOCKHEED MISSILES & SPACE COMPANY, INC.
A SUBSIDIARY OF LOCKHEED AIRCRAFT CORPORATION

REPCRT 1961

8 July 1982

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ENGINEERING TEST REPORT
SPECTRUM ANALYSIS OF OM3-3 AND OM4B
EQUIPPED WITH BRYANT 18,000 rpm SPINDLE

Prepared by: L. W. Martin
L. W. Martin

Checked by: T.O. Rainforth
T.O. Rainforth

Approved by: R. R. Walton
R. R. Walton
Group Engineer, 85-74

B-1

SUMMARY OF RESULTS/CONCLUSIONS:

A vibration spectrum analysis of the Bryant 18,000 rpm spindle mounted in the OM3-3 in Bldg. 170 and in the OM4B in Bldg. 182 was performed. The spindle was operated both with and without tools. The 1-1/4 inch diameter tool exhibited a minimum vibration level at 18,000 rpm while the 4.0 inch diameter tool minimum vibration level was at 8,000 rpm in the OM3-3. These speeds were successfully used to machine the NASA Space Shuttle Integral Stiffner Panels.

REFERENCES:

Test Authorization: TM T26595 High Speed Machining of
NASA Shuttle Tank Integral I Beam Panels

Test Procedure: Op Order 15146

Test Start/Completion Dates: 5-12-82/6-9-82

Reference Documents: Test Report 1736

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A SUBSIDIARY OF LOCKHEED AIRCRAFT CORPORATION

REPCRT 1961

Page 2

I. Objective

The objective of this task was to determine the rotational vibrations and resonances of the Bryant 18,000 rpm spindle mounted in both the OM3-3 in Bldg. 170 and in the OM4B in Bldg. 182. The OM3-3 was used for cutter trials and the OM4B was used for cutting integral stiffner demonstration panels for the NASA Shuttle Tank High Speed Machining Test.

II. Test Spindle and Tools

The spindle tested was the Bryant 18,000 rpm direct drive spindle motor mounted in the Sundstrand OM3-3 in Building 170 and in the OM4B in Building 182. Tools tested consisted of a high speed steel, three flute 1-1/4 inch diameter cutter and a 4.0 inch diameter brazed insert cutter.

III. Test Procedure

An Endevco 2236 accelerometer was mounted radially on the face of the Bryant spindle. The accelerometer output was amplified by an Endevco Model 2735 charge amplifier and analyzed by a Schlumberger 1510 real time analyzer. The vibration data was recorded on an HP X-Y recorder.

The spindle was installed in the OM3-3 without a tool and operated at speeds from 6000 to 18,000 rpm. Data was taken at 2000 rpm intervals. This data is plotted in Figure 1. The data for the 1-1/4 inch and 4 inch diameter cutters is shown in Figures 2 and 3. The 1-1/4 inch diameter showed a minimum vibration level at 18,000 rpm and the 4.0 inch diameter cutter had less vibration at 8000 rpm. Tool tryout cuts were made at these speeds using this setup in the OM3-3.

The spindle was moved to the OM4-2 in Bldg. 182. The rpm spectral map for the empty spindle in this machine tool is shown in Figure 4. The data for the 1-1/4 inch and the 4.0 inch diameter cutters is shown in Figures 5 and 6.

The tool test data appears similar to that obtained in the OM3 except that the 1-1/4 inch cutter vibration level minimum was at 16,000 rpm. Successful demonstration cuts were made at 18,000 rpm using the 1-1/4 inch cutter and at 8000 rpm with the 4.0 inch diameter cutter. The table feed rate was 200 in/min.

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cc: J. A. Miller 86-61/170

B-3

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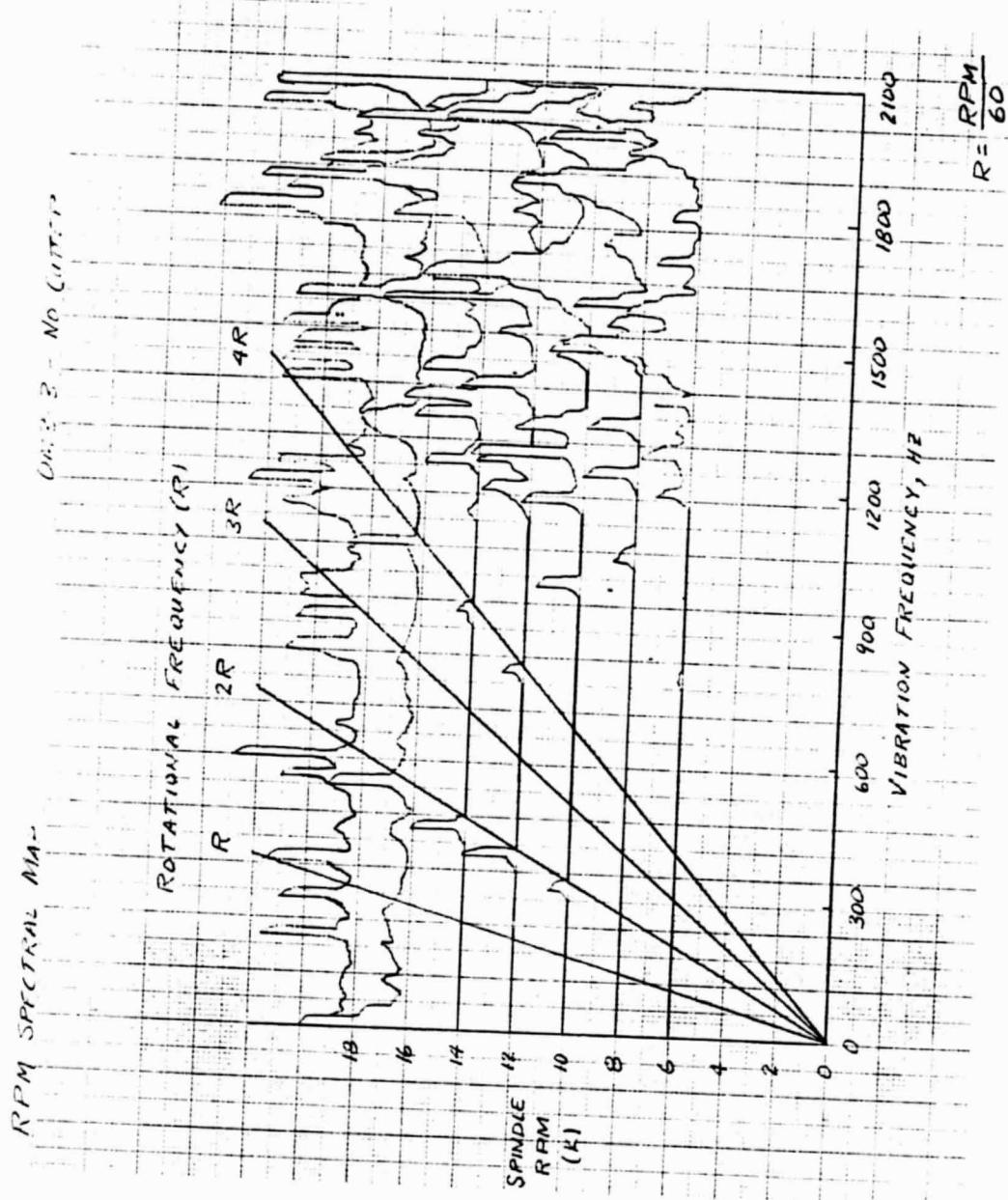


Figure B-1

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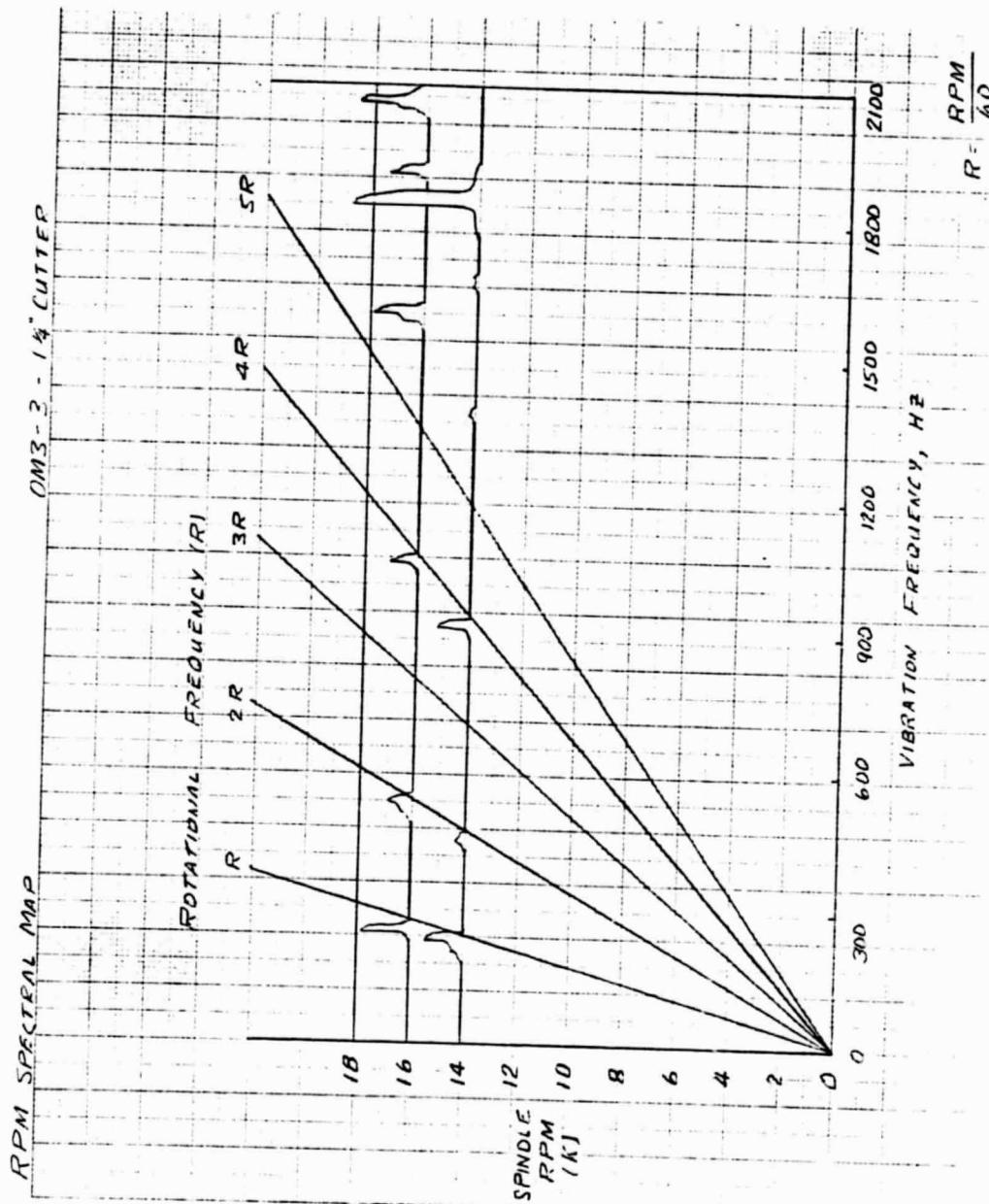


Figure B-2

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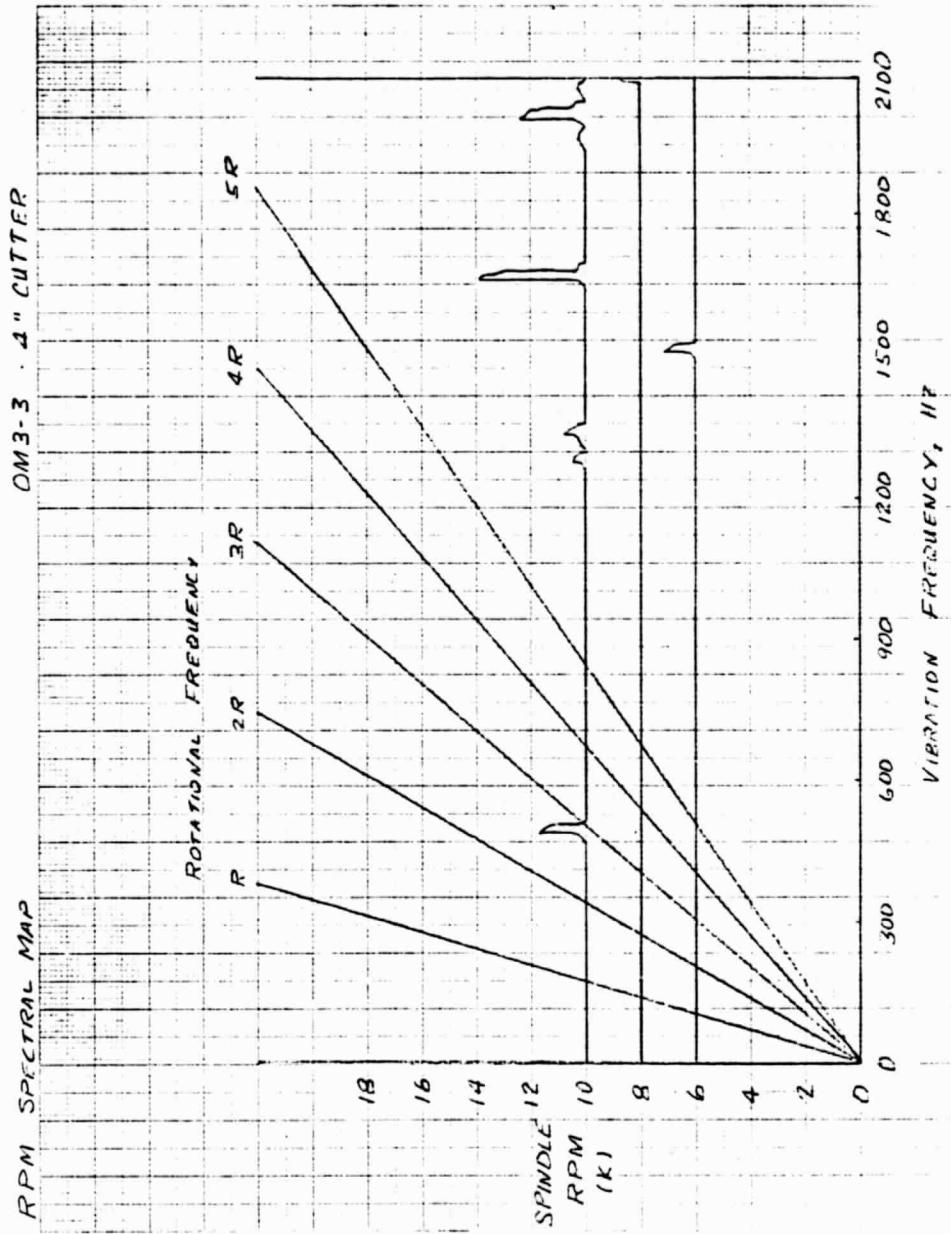


Figure B-3

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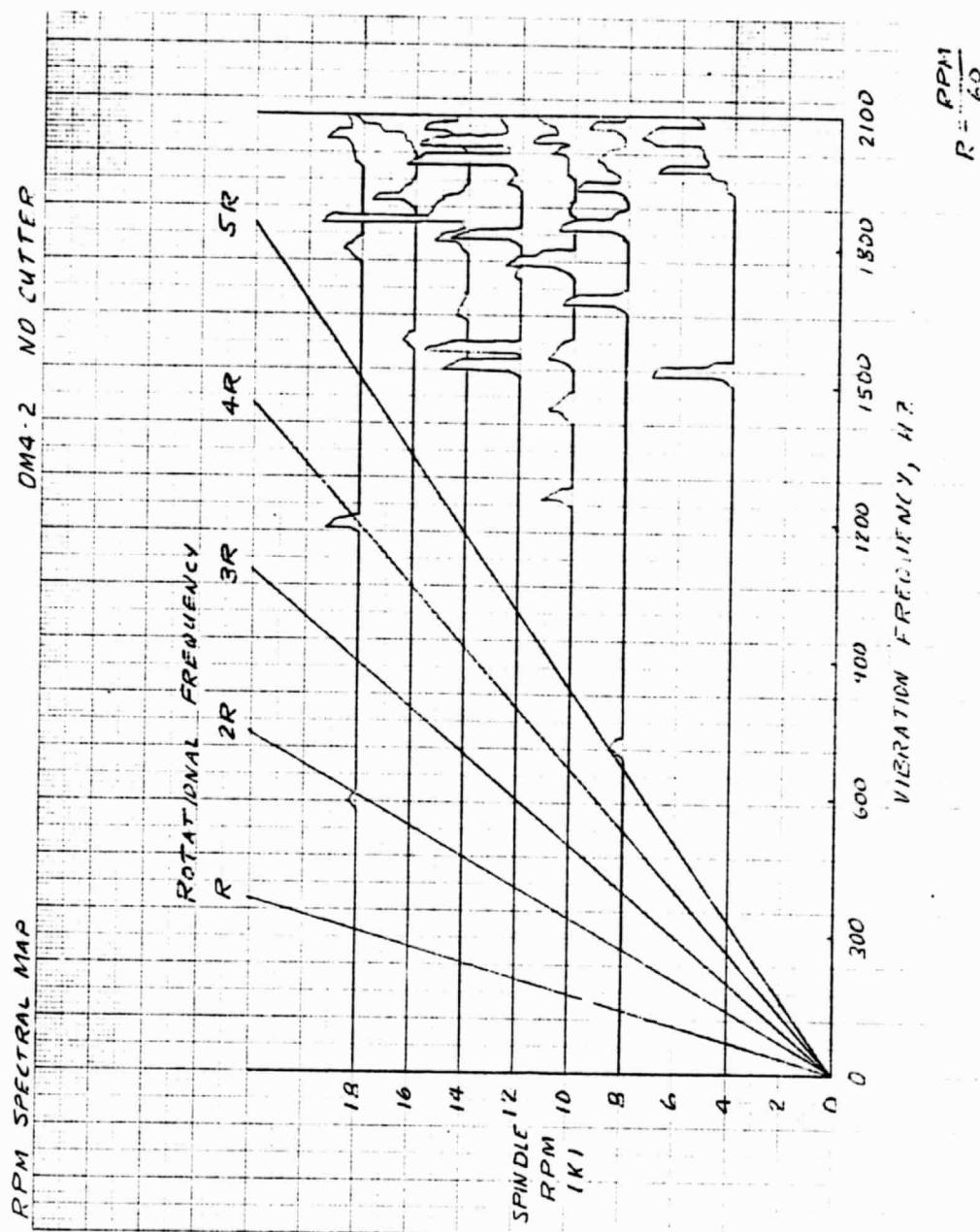


Figure B-4

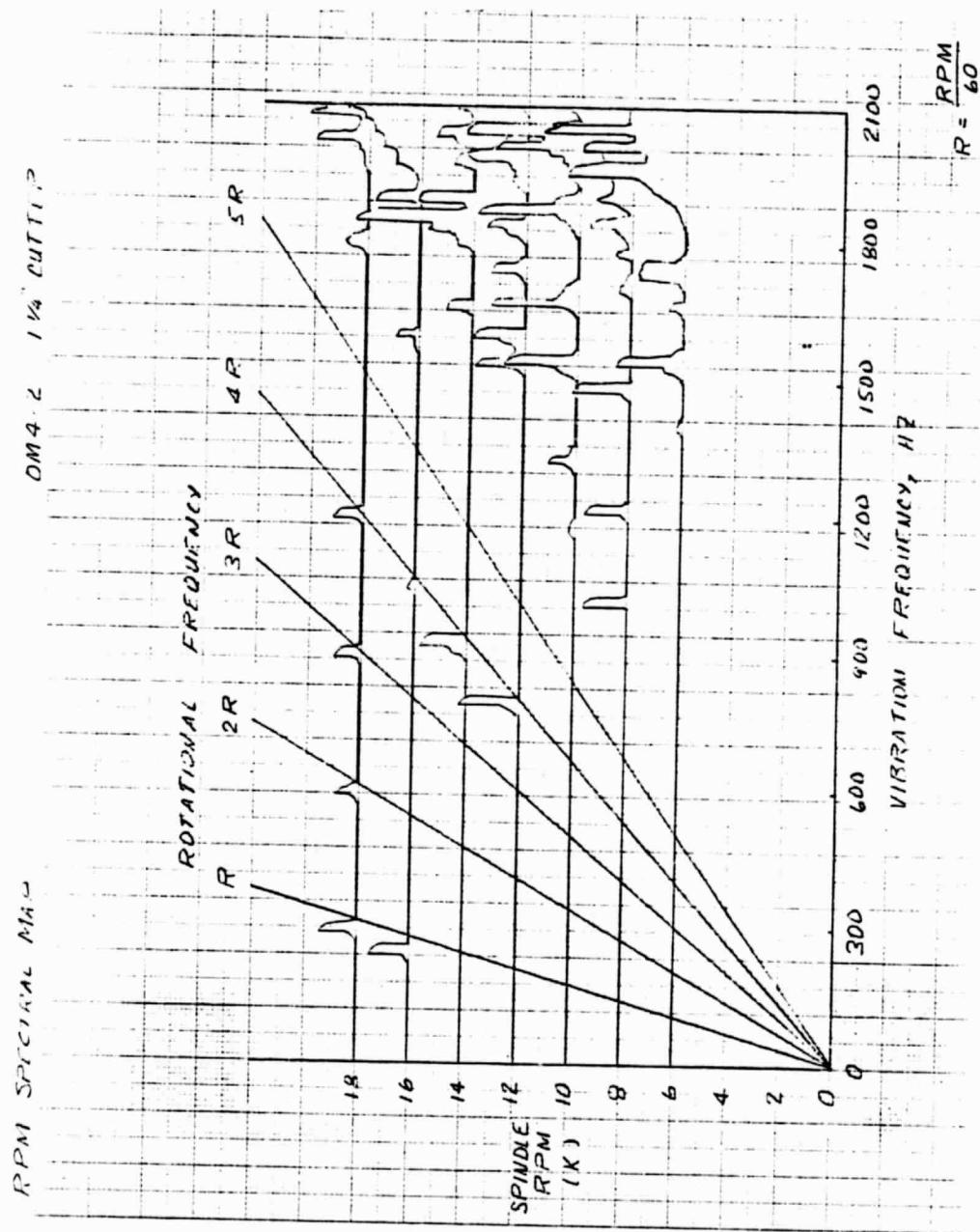
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Figure B-5

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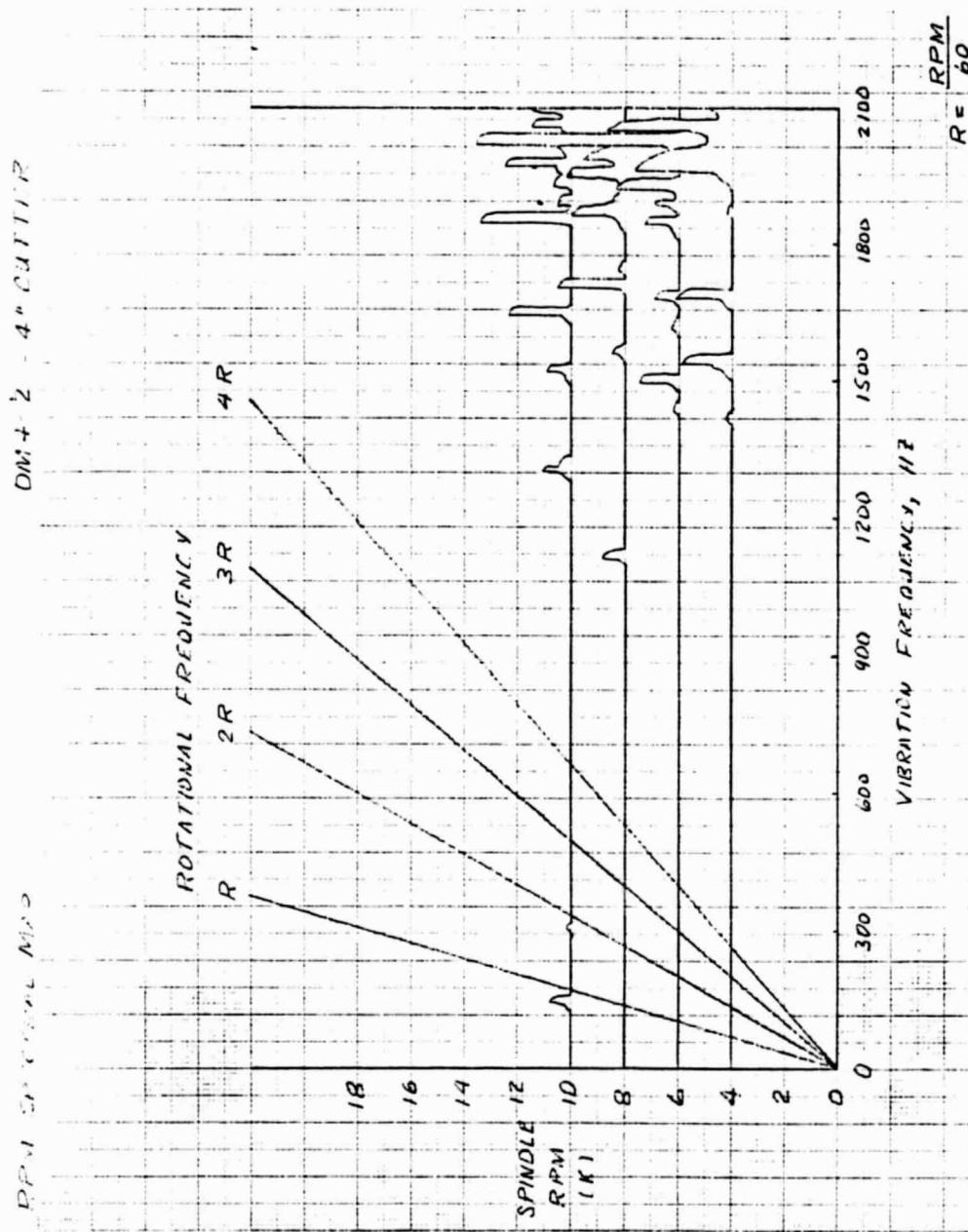


Figure B-6

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APPENDIX C

Attendees at NASA Shuttle Tank High-Speed Machining Demonstration
June 15, 1982, B/181 and B/182

NASA Marshall Space Flight Center (MSFC)

Edward J. Bryan
Paul H. Schuerer

Martin Marietta

Gerry Scott
R. G. "Bob" Williams
Steven A. DeLony

Cleveland Pneumatic Company

John A. Wulf

Reynolds Metals Co.

R. J. "Bob" Kazmier

U. S. Navy - Sunnyvale

Mike Maionchi

LMSC

Robert I. King
A. J. Kish
J. A. Miller
E. A. "Gar" Eger
C. Gallman
R. N. Johnson
I. M Suarez
M. I. Jacobson

APPENDIX D

AGENDA

HIGH SPEED MACHINING OF SPACE SHUTTLE
EXTERNAL TANK PANELS
PANEL CUTTING DEMONSTRATION

June 15, 1982

- 8:15 a.m. Arrive in Bldg. 181 Lobby
- 8:30 a.m. Welcome (Navy Conference Rm. B) - Joe Miller, Program Manager
MSD Background - Sam Dollar, Mgr., Manufacturing Program Support
- 8:50 a.m. High-Speed Machining Concepts & Contract Briefing - Joe Miller
- 10:00 a.m. Panel Cutting Demonstration
(Sundstrand OM4B, B/182, Column E23)
- 11:30 a.m. Lunch in Cafeteria (Bldg. 149)
- 12:45 p.m. Panel Cutting Demonstration - continued
- 1:45 p.m. Discussion Period - (Navy Conference Room B)
- 3:00 p.m. Tour of LMSC Space Shuttle Tile Fabrication Facility (Bldg. 174)
- 4:00 p.m. Return to Bldg. 181 Lobby

APPENDIX E

SETUP AND OPERATING INSTRUCTIONS

FOR

MACHINING 4 FT LONG PANELS

SETUP & OPERATING INSTRUCTIONS

1. Load NAS 8664 fixture onto OM-4 table and secure.
2. Load shuttle No. 1 tape into reader. Set block delete off and cycle tape.
3. Program stop. Indicate left locating pin. Retract "Z" axis and cycle tape.
4. Program stop. Indicate right locating pin. Home "Z" axis and cycle tape.
5. Program stop. Load part per sketch on page 3. Set block delete on and cycle tape.

<u>SEQ. NO.</u>	<u>OPERATIONS</u>	<u>TOOL NO.</u>
	Program stop. Touch off, on top of part using a 1.000 feeler. Cycle tape.	02
010	Mill .126 Dim.	02
020	Mill .126 Dim.	02
030	Mill .126 Dim.	02
040	Mill .320 Dim. and .141 Dim.	02
	Program stop. Touch off, on .126 Dim. using a 1.000 feeler. Cycle tape.	03
050	Mill .37 corner radius.	03
	Program stop. Touch off, on .126 Dim. using a 1.000 feeler. Cycle tape.	04
060	Mill under flange.	04

END OF PROGRAM.

<u>TOOL NO.</u>	<u>TYPE</u>	<u>RPM</u>	<u>F/R</u>
02	1.250 Dia. E.M. .060 R.	18,000	150-200
03	1.250 Dia. E.M. .370 R.	18,000	180
04	4.000 Dia. Wheel Cutter .125 R.	8,000	40-100

CUTTING DATA

<u>TOOL NO.</u>	<u>DEPTH OF CUT</u>	<u>WIDTH OF CUT</u>	<u>CUBIC INCHES</u>
02	.070-.300	1.1-1.250	18-56
03	.370	.370	25
04	.075-.635	.025-.550	18

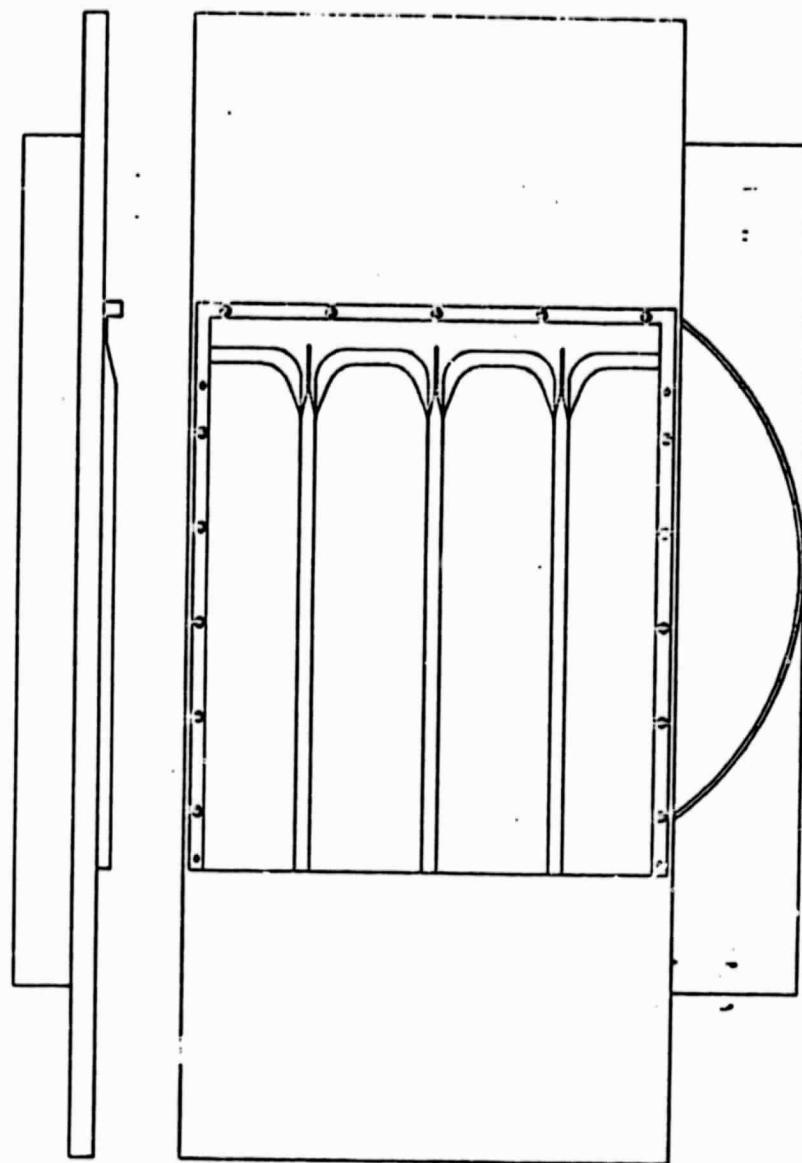
<u>TOOL NO.</u>	<u>SFM</u>	<u>CHIP LOAD</u>
02	5,890	.0025-.0032
03	5,890	.003
04	8,378	.0016-.0032

E-3

SHUTTLE-SHORT-1	
REV	Page 2 of 4

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APPENDIX E



APPENDIX E

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SUNDSTRAND OMNIMILL 4X

CHART OF DIMENSIONS FROM HOME OR MACHINE ZERO. POSITION FOR SEQNO OR TMARK.

SEQNO.	X-DIMENSION	Y-DIMENSION	Z-DIMENSION	A-DIMENSION	C-DIMENSION	SPINDLE	TOOL NO.	HEAD
010	53.0000	-46.0000	-21.3750	25.0000	.0000			2 HIGH
020	26.0000	-47.0000	-21.3750	25.0000	.0000	S635 M17	2	HIGH
030	26.0000	-56.0680	-21.3750	25.0000	.0000	S635 M17	2	HIGH
040	64.4690	-63.5050	-21.8750	25.0000	.0000	S635 M17	2	HIGH
050	53.0000	-49.9590	-21.8750	25.0000	.0000	S635 M17	3	HIGH
060	53.0000	-50.2715	-20.0000	25.0000	.0000	S635 M17	4	HIGH

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APPENDIX F

(FIRST HALF) LL2 No.1

HIGH SPEED MILLING DATA SHEET

FOR 8 FT LONG PANEL NO. LL2

TOOL # 02.126 DIM.

PASS	Z AXIS	DEPTH	FEED RATE	RPM	H/P
1	-22.6750	.300	150	18000	13.4
2	-22.9750	.300	150	18000	13.5
3	-23.2750	.300	150	18000	13.3
4	-23.5750	.300	150	18000	13.4
5	-23.6290	.054	200	18000	7.2
6	-23.9290	.300	150	18000	12.0
7	-23.9990	.070	200	18000	7.4
1	-22.6750	.300	150	18000	13.4
2	-22.9750	.300	150	18000	13.8
3	-23.2750	.300	150	18000	13.1
4	-23.5750	.300	150	18000	13.2
5	-23.6290	.054	200	18000	7.1
6	-23.9290	.300	150	18000	13.3
7	-23.9990	.070	200	18000	7.8

.320 DIM.

1	-22.6750	.300	150	18000	13.4
2	-22.9750	.300	150	18000	12.5
3	-23.2750	.300	150	18000	12.8
4	-23.4350	.160	200	18000	10.0
5	-23.7350	.300	150	18000	13.4
6	-23.8050	.070	200	18000	1.8
1	-22.6750	.300	150	18000	12.3
2	-22.9750	.300	150	18000	13.0
3	-23.2750	.300	150	18000	10.9
4	-23.4350	.160	200	18000	10.3
5	-23.7350	.300	150	18000	13.4
6	-23.8050	.070	200	18000	6.8

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APPENDIX F

(FIRST HALF) LL2 No.1

HIGH SPEED MILLING DATA SHEET FOR 8 FT LONG PANEL NO. LL2

TOOL # 02.141 DIM.

PASS	Z AXIS	DEPTH	FEED RATE	RPM	H/P
1	-23.9840	.179	200	18000	6.2
1	-23.9840	.179	200	18000	6.2
1.250 DIM.					
1	-22.6750	.300	150	18000	8.1
2	-22.8750	.200	200	18000	8.0
1	-22.6750	.300	150	18000	13.4
2	-22.8750	.200	200	18000	10.2

TOOL # 03.126 DIM.

1	-23.9990	.370	180	18000	8.4
.141 DIM.					
1	-23.9840	.370	180	18000	8.4
.320 DIM.					

1	-23.8050	.370	180	18000	8.4
.141 DIM.					
1	-23.9840	.370	180	18000	8.2
.141 DIM.					

TOOL # 04

1	-21.8090	.635	40-50	8000	5.1
2	-21.6350	.150	100	8000	3.7
3	-21.9840	.150	100	8000	3.9

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APPENDIX F

(SECOND HALF) LL2 No.2

HIGH SPEED MILLING DATA SHEET

FOR 8 FT LONG PANEL NO. LL2

TOOL # 02.126 DIM.

PASS	Z AXIS	DEPTH	FEED RATE	RPM	H/P
1	-22.6750	.300	150	18000	12.8
2	-22.9750	.300	150	18000	12.4
3	-23.2750	.300	150	18000	12.5
4	-23.5750	.300	150	18000	12.6
5	-23.6290	.054	200	18000	12.8
6	-23.9290	.300	150	18000	12.8
7	-23.9990	.070	200	18000	12.2
1	-22.6750	.300	150	18000	12.7
2	-22.9750	.300	150	18000	12.4
3	-23.2750	.300	150	18000	12.4
4	-23.5750	.300	150	18000	12.4
5	-23.6290	.054	200	18000	12.7
6	-23.9290	.300	150	18000	12.4
7	-23.9990	.070	200	18000	12.3

.320 DIM.

1	-22.6750	.300	150	18000	12.9
2	-22.9750	.300	150	18000	12.9
3	-23.2750	.300	150	18000	12.1
4	-23.4350	.160	200	18000	10.0
5	-23.7350	.300	150	18000	12.4
6	-23.8050	.070	200	18000	7.1
1	-22.6750	.300	150	18000	13.6
2	-22.9750	.300	150	18000	12.8
3	-23.2750	.300	150	18000	12.5
4	-23.4350	.160	200	18000	10.2
5	-23.7350	.300	150	18000	12.5
6	-23.8050	.070	200	18000	7.0

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APPENDIX F

(SECOND HALF) LL2 No.2

HIGH SPEED MILLING DATA SHEET FOR 8 FT LONG PANEL NO. LL2

TOOL # 02					
<u>.141 DIM.</u>					
PASS	ZAXIS	DEPTH	FEED RATE	RPM	H/P
1	-23.9840	.179	200	18000	10.2
1	-23.9840	.179	200	18000	10.2
<u>1.250 DIM.</u>					
1	-22.6750	.300	150	18000	12.7
2	-22.8750	.200	200	18000	10.8
1	-22.6750	.300	150	18000	12.6
2	-22.8750	.200	200	18000	10.6
TOOL # 03					
<u>.126 DIM.</u>					
1	-23.9990	.370	180	18000	8.3
<u>.141 DIM.</u>					
1	-23.9840	.370	180	18000	8.4
<u>.320 DIM.</u>					
1	-23.8050	.370	180	18000	8.3
1	-23.8050	.370	180	18000	8.4
<u>.141 DIM.</u>					
1	-23.9840	.370	180	18000	8.2
TOOL # 04					
1	-21.8090	.635	40-50	8000	5.2
2	-21.6350	.150	100	8000	4.1
3	-21.9840	.150	100	8000	7.8